

# **OPTIMAL USAGE OF DE-ICING CHEMICALS WHEN SCRAPING ICE**

## **Final Report of Project HR 391**

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by

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# **CHAPTER 1**

## **INTRODUCTION**

One of the challenges that faces the winter maintainer is how much chemical to apply to the road under given conditions. Insufficient chemical can lead to the road surface becoming slick, and the road thus becoming unsafe. In all likelihood, additional applications will have to be made, requiring additional effort and use of resources. However, too much chemical can also be bad. While an excess of chemical will ensure (in most circumstances) that a safe road condition is achieved, it may also result in a substantial waste of chemical (with associated costs for this waste) and in ancillary damage to the road itself and to the surrounding environment. Ideally, one should apply what might be termed the “goldilocks” amount of chemical to the road: Not too much, and not too little, but just right.

Of course the reality of winter maintenance makes achieving the “goldilocks” application rate somewhat of a fairy tale. In the midst of a severe storm, when conditions are poor and getting worse, the last thing on a plow operator’s mind is a minute adjustment in the amount of chemical being applied to the road. However, there may be considerable benefit and substantial savings to be achieved if chemical applications can be optimized to some degree, so that wastage is minimized without compromising safety. The goal of this study was to begin to develop such information through a series of laboratory studies in which the force needed to scrape ice from concrete blocks was measured, under a variety of chemical application conditions.

One of the more severe conditions that has to be dealt with in winter highway maintenance occurs when ice has adhered to the pavement surface. This situation is complicated by a number of factors. The ice in question may have formed in a number of ways, and its behavior may be dependent upon how it was formed. Certainly, the mode of ice formation will affect the crystalline structure of the ice, and it is known that ice microstructure effects the fracture resistance of the ice (Weber and Nixon, 1996 a, b). Accordingly, the optimal method for removing ice from the pavement may depend upon how the ice got there in the first place.

Ice may appear on the road as compacted snow ice, refrozen ice, or atmospheric ice. The modes of formation of these three ice types are as follows. Compacted snow ice forms when snow is compacted onto the pavement by the passage of vehicles, especially when the pavement surface is wet. This compaction increases the density of the snow pack, until it becomes essentially ice-like. Refrozen ice forms when snow at the side of the road melts, and then flows across the road surface, refreezing in the process. Atmospheric ice can form either as freezing rain, or as sleet. Freezing rain occurs when the precipitation falls as water, but freezes upon contact with the (below freezing) pavement surface. Sleet forms when the precipitation itself has gone through at least one melt and refreeze cycle during the falling process. These ice types are different in microstructure, mechanical behavior, and adhesion to the road surface (Nixon et al., 1997).

However, reports on the effects of ice type on the removal of ice from pavements are rare. Kinoshita and Akitaya (1970) reported that snow and ice on roads can appear in different forms, and moreover change continuously under the action of traffic and weather. They attempted to classify the types of snow and ice according to density, hardness, and soil content of the snow and ice samples taken from the roads. However, they made no effort to relate these snow and ice types to the ease (or otherwise) with which they can be plowed from the pavement.

In addition to examining how ice type effects the extent to which ice adheres to the pavement, this study also examined how various rates and types of de-icing chemical application effects the scraping resistance of ice on the pavement. Specifically, solid salt (Sodium Chloride), solid Calcium Chloride, and a liquid salt solution or brine were tested at different quantities of application, and also for differing delay times after application prior to scraping. It is well known that de-icing chemicals cause ice to melt. However, there are no data that indicate how application of such chemicals weakens ice strength, and specifically, how much such chemicals make ice easier to scrape from the pavement. De-icing chemicals are not applied with the intent of melting all the snow and ice on the pavement – such would require prohibitive quantities of chemicals be applied. The aim of such applications is to break the bond between ice and pavement, and thus make

scraping away of the ice easier. This study aims to address this issue and begin the process of developing meaningful data on this issue.

The effect of ice type on the removal of ice from concrete pavements has been investigated in this study through a series of laboratory ice scraping tests. The tests were performed using a scraping machine installed in a cold room at the Iowa Institute of Hydraulic Research (IIHR). Further details of the test machine, the concrete specimens and the sample preparation methods are given in Chapter 2. Chapter 3 presents the experimental results. Chapter 4 discusses the implications of these results, and how the results might influence winter maintenance activities. Chapter 5 presents the conclusions of the study.

## CHAPTER 2

### METHOD

#### 2.1 Test Equipment and Specimens

The experiments in this project examined the resistance of ice to being scraped from a pavement surface. The ice was formed (see section 2.2) on concrete specimens, that were 4 inches by 12 inches (10 cm by 30 cm) in top surface area, and about 6 inches (15 cm) deep. The specimens were made from an Iowa DOT PCC C-4 mix, in order to best model a typical road surface. Specimens were formed in specially built molds. While the concrete was still viscous, the top surface of each concrete specimen was roughened with a brush. Figure 2.1 shows a typical concrete test specimen (with ice on the testing surface). The concrete specimens are described more fully in Nixon et al. (1996).



Figure 2.1: Typical Concrete Test Specimen

The testing machine used in the experiments is comprised of a hydraulic ram that scrapes the concrete specimens across a cutting edge. The ram is controlled so that a



desired velocity can be achieved during a given test. The cutting edge is instrumented using a three-axis load cell, so that forces in three orthogonal directions (along the direction of travel, and two perpendicular axes that are both perpendicular to the direction of travel) can be measured and recorded. Data are collected using a PC based data acquisition system. The test ram is capable of scraping at speeds up to 30 mph (48 kph) but in this study scraping speeds were kept to 6 mph (9.6 kph) to minimize vibrations of the cutting edge. This velocity had been found to be a good representative velocity on the basis of previous studies (Nixon, 1993; Nixon et al., 1996). A more complete description of the scraping machine can be found in Nixon (1993) and Nixon and Chung (1992).

## **2.2 Formation of Ice Types**

In order to prepare specimens that had repeatable ice types on them, a method had to be developed for each of the three ice types tested in the project. These methods are described below, but they share some similarities. In all cases, the concrete specimens were placed in the cold room at IIHR for 24 hours prior to ice formation, to ensure that the concrete samples had come to a uniform temperature. Care was taken to minimize sublimation during the freezing process, by protecting the specimens from air currents. After ice had been placed on the concrete specimen, the specimens were always left overnight and tested the following day.

Specimens were tested at three different temperatures ( $-1^{\circ}\text{C}$ ,  $-5^{\circ}\text{C}$  and  $-20^{\circ}\text{C}$ ). With one exception (noted below) samples were made at the same temperature at which they were tested.

### **2.2.1 Refrozen Ice**

The first stage of specimen preparation for this ice type was to create a “dam” around the top of the concrete specimen. This was done using 25 mm wide strapping tape. The dam was carefully set to a height of 10 mm above the concrete specimen surface (so that the ice depth would be 10 mm). Water (at close to  $0^{\circ}\text{C}$ ) was then added in “lifts” of approximately 1 mm, until the dam was filled. Between 15 minutes and half

an hour elapsed between additions of water (depending on temperature). After being left overnight, the strapping tape was removed, and samples were ready for testing.

### **2.2.2 Atmospheric Ice**

As described above, a dam was formed around the top of each concrete specimen, to a depth of 10 mm. The twelve testing specimens were then placed close to each other, side by side. A pump and spray system was used to produce a fine water mist over the surfaces of the concrete specimens, which simulated atmospheric icing of the road surface. The spraying was halted when all samples had the desired thickness of spray ice. Again, after being left overnight, the strapping tape was removed and the samples were ready for testing.

For the specimens to be tested at  $-1^{\circ}\text{C}$ , it was too warm for the water mist to freeze quickly enough on the concrete specimen surface. Therefore, spraying for these specimens took place at  $-5^{\circ}\text{C}$ , and once the spray ice had formed, the cold room temperature was adjusted to  $-1^{\circ}\text{C}$ , and the samples were left overnight to equilibrate in temperature.

### **2.2.3 Compacted Snow Ice**

For these samples, a sturdier “dam” had to be formed. Steel collars (as opposed to strapping tape) were attached around the top of the samples. Snow was harvested during the winter, and stored until needed. After sieving, a uniform depth of snow was placed inside the steel collar. This was then compressed under a load of 4,000 lbs for ten minutes (at the test temperature) using an MTS Servohydraulic testing machine in the IIHR cold rooms. After compression, samples were sprayed with water (at  $0^{\circ}\text{C}$ ). The samples were then left overnight at the testing temperature. The following day the steel collars were removed and samples were ready for testing.

## **2.3 Chemical Testing**

Three different chemical applications were examined in the study: Solid Sodium Chloride, solid Calcium Chloride, and a liquid salt brine (27.3% by weight of Sodium

Chloride in water). The ice samples tested were all refrozen ice, made according to the method described in Section 2.2.1 above. This method of preparation produces an ice that is relatively bubble free. It was important that the ice not have many bubbles, as bubbles act as small cavities in the ice and may substantially accelerate the penetration of the chemical into the ice. Also, since the preparation method produced a somewhat uneven top surface, the ice was milled flat on these specimen prior to chemical application.

Preliminary testing indicated that at least four grams of chemical (which translates to 14 grams of brine) had to be applied to each sample to ensure repeatable and reliable results. If less chemical was applied, there was substantial variation from test to test. This rate of application corresponds to a field application rate of 1760 lbs per lane mile (or 130 grams per square meter) which is obviously a very heavy rate of application (300 to 400 lbs per lane mile would be a more usual application rate of dry or pre-wet chemical).

In order to ensure that chemical was applied as uniformly as possible over the ice surface, the solid chemicals were ground to a fine powder (all particles passing a 1mm sieve) and dusted evenly onto the surface. In addition to varying the chemical types, tests were run with four different delay times of 10, 20, 30, and 40 minutes. The delay time was the time between application of the chemical and the time of testing. All chemical tests were conducted at a temperature of  $-5^{\circ}\text{C}$ .

## **2.4 Scraping Tests**

As noted above, all specimens were tested using the hydraulic ram scraping machine. This testing apparatus is placed in one of the cold rooms at IIHR. Temperatures in this room can be controlled to  $\pm 0.1^{\circ}\text{C}$ . The specimens were placed in the same room as the testing apparatus for specimen preparation and equilibrating prior to testing.

#### **2.4.1 General Test Conditions**

The cutting edge in the scraping test was one that had been shown to be particularly representative of field behavior, as determined in Nixon et al. (1996). This cutting edge had a rake angle of 30° and a clearance angle of 5°. The scraping speed for all tests was 6 mph (or 9.6 kph). In all cases, the thickness of ice being scraped was 10 mm.

#### **2.4.2 Specimen Labeling for Ice Type Tests**

As noted above, each ice type was tested at three temperatures. Between six and twelve specimens were tested under each condition. Specimens were given the label DX-xx. The D indicated that this test series was devoid of chemicals. The X indicated the ice type being tested. An “F” indicated refrozen or pooled ice. An “S” indicated spray or atmospheric ice. A “C” indicated compacted frozen snow. The xx was a number between 1 and 36, which indicated the test temperature. Specimens numbered between 01 and 12 were tested at –1°C. Specimens numbered between 13 and 24 were tested at –5°C. Specimens numbered between 25 and 36 were tested at –20°C. Thus the specimen labeled DS-19 was a specimen with atmospheric ice, tested at –5°C.

#### **2.4.3 Specimen Labeling for Chemical Tests**

As noted above, all chemical specimen tests were conducted at –5°C. The cutting edge and scraping velocity were the same as those for the ice type tests. Specimens were labeled as X4xx-y. The X indicated the type of chemical being tested. An “S” indicated that solid Sodium Chloride was the chemical. A “C” indicated solid Calcium Chloride. A “B” indicated that the chemical tested was brine (a 27.3% solution of Sodium Chloride in water). The xx indicated the delay time and had four different values (10, 20, 30 and 40) corresponding to the delay in minutes between chemical application and testing. The y was a specimen number for that test. Three different samples were tested for each condition of chemical type and delay time.

## 2.5 Density Measurements

The different ice types being tested were characterized in two ways, by their density and by their microstructure. Table 2.1 shows the densities obtained for the three different ice types. Densities were obtained by weighing samples of the ice type in air and in a liquid (iso-octane). The densities are given in units of  $\text{kg m}^{-3}$ .

**Table 2.1 Ice Type Density Measurements**

Specimen	Refrozen Ice	Atmospheric Ice	Compacted Snow
1	0.90	0.88	0.73
2	0.92	0.88	0.75
3	0.90	0.88	0.62
4	0.88	0.84	0.64
5	0.92	0.84	0.72
<b>Average Value</b>	<b>0.90</b>	<b>0.86</b>	<b>0.69</b>

From Table 2.1 it is apparent that the compacted snow has a significantly lower density than either the refrozen ice or the atmospheric ice. This is not unexpected. Densification of snow is rapid immediately after a snowfall, but it can take many years (in a glacier for example) for such snow to approach the full density of ice.

Micrographically the refrozen ice has a much larger grain size than either the atmospheric ice or the compacted snow. The grain size of these latter two ice types was so small that standard thin section did not show the grains. Figure 2.2 shows a thin section of the refrozen ice. Grains are irregularly shaped and range in size up to 20 mm.

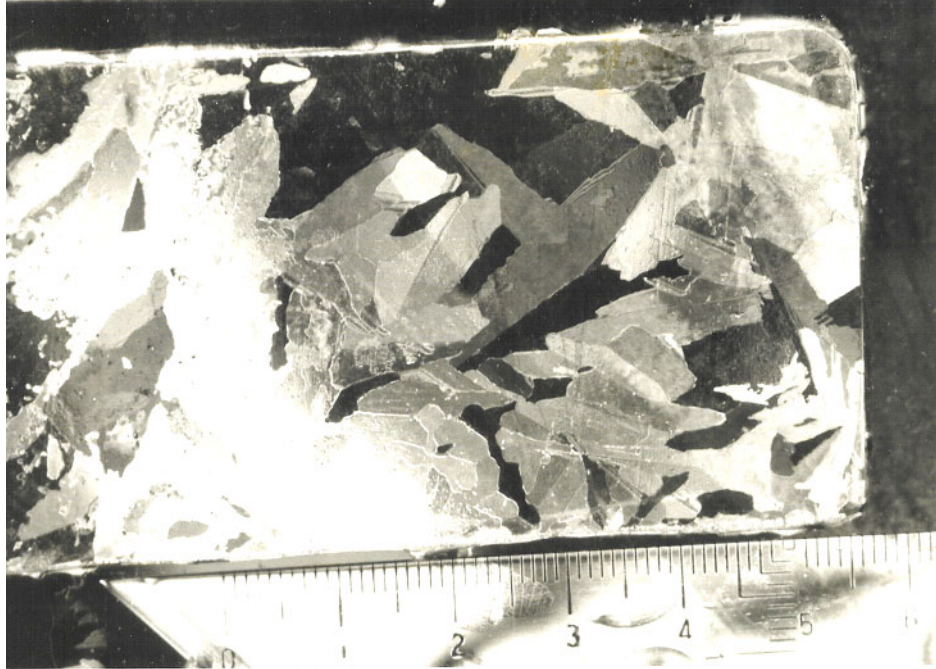


Figure 2.2: A thin section of the refrozen ice, seen through crossed polarizing filters, and showing individual crystals in the ice.

## CHAPTER 3

### RESULTS

#### 3.1 General Information on Test Data

The results of the scraping tests are presented in two parts. First, the results of the ice type tests (see section 2.4.2) are given. Then the results of the chemical tests (2.4.3) are given. A primary concern for all test types was determining a method by which a “successful” test could be identified. Data were collected from each test using a data acquisition system (PC Based) that collected data at a frequency of 500 Hz. Two different loads (termed  $F_x$  and  $F_z$ ) were recorded for each test.  $F_z$  is the actual (horizontal) scraping force.  $F_x$  is the downforce required to keep the blade scraping the ice. Sometimes, the downforce would become negative, indicating that the cutting edge was “digging into” the ice surface, but more normally, the downforce remained positive during the test. Most tests indicated ice being scraped for about 140 milliseconds (ms).

Figure 3.1 shows a successful test (in this case, for sample DF-01 – refrozen ice tested at  $-1^{\circ}\text{C}$ ). Data were collected from about 0.190 seconds to about 0.330 seconds. The extremely “ragged” nature of the two time series during the ice scraping is typical of brittle failure, indicating sudden load drops as pieces of ice were broken from the surface. In contrast, Figure 3.2 shows an unsuccessful test (for sample DS-18 – spray ice tested at  $-5^{\circ}\text{C}$ ). The loads are very low and in fact are not statistically different from zero load. In this case, test observation indicates that very little load was needed to separate the whole ice cover from the concrete test specimen. Why this ice was so poorly bonded to the concrete for this specimen is not known, especially as other test specimens from the same lot (e.g. DS-16 see Appendix A) required substantial scraping loads. However, Figure 3.2 is an easy case to determine, since loads are so low. Some form of discriminating test must be applied to the data to determine which time series are “good” and which should be discarded. Simply to say, “this test looks good and this one doesn’t,” is not acceptable.

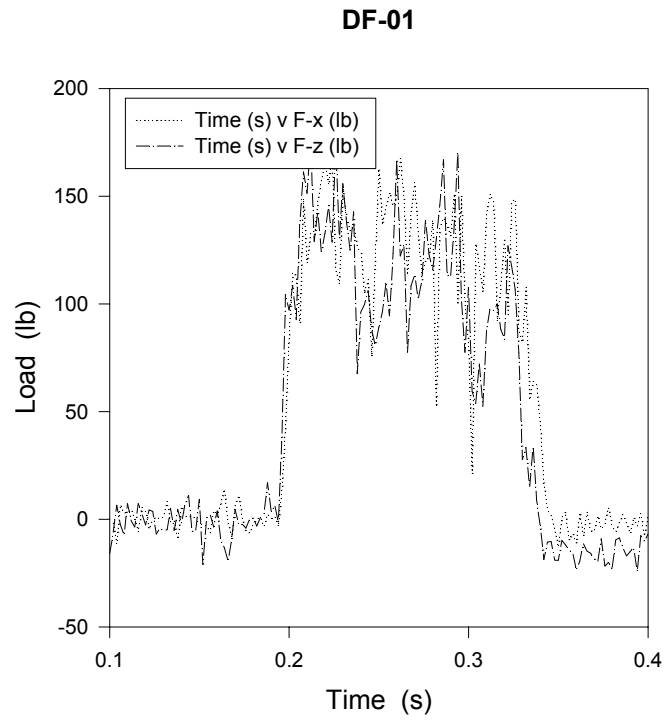


Figure 3.1: A Test Defined as Successful (Sample DF-01)

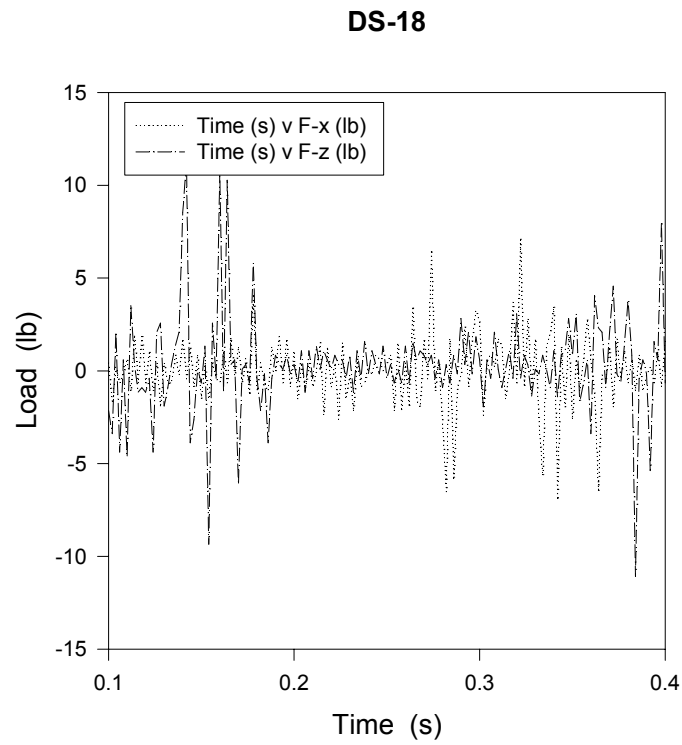


Figure 3.2: A Test Defined as Unsuccessful (Sample DS-18)



After reviewing the data, it was decided that a simplified form of statistical t-test would be the best way to discriminate acceptable tests. In essence, this test requires that there be greater than 95% confidence that the observed loads in the test are different from zero. This test is easy to make, insofar as if the standard deviation of the time series exceeds the mean of the time series during the scraping time period, then the load is not statistically different from zero at the 95% level of confidence. Thus, if either of the two loads (Fx or Fz) has a standard deviation greater than its mean for a test, then that test was discarded as being not meaningful. Figure 3.3 shows an example of such a test (test DS-06 for spray ice at  $-1^{\circ}\text{C}$ ).

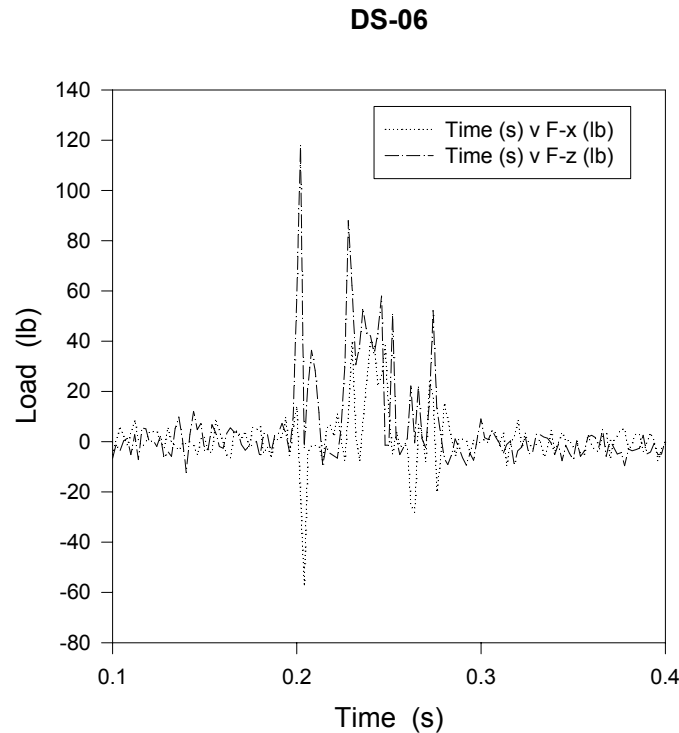


Figure 3.3: An Unsuccessful Test According to the 95% Confidence Level Definition (Sample DS-06)

### 3.2 Results from Ice-Type Tests

As indicated above, a total of 108 tests were performed on three different ice types. Table 3.1 indicates the successful tests (using the definition given above). Of the three ice types, refrozen ice was the easiest to obtain good tests, while the compacted snow was hardest. Further, it was most difficult to obtain good tests at the warmest test temperature ( $-1^{\circ}\text{C}$ ). All successful test data are shown in Appendix A and tabulated data for these tests are given in Appendix B.

**Table 3.1 Successful Tests for Ice Type Test Series**

Ice Type	Sample numbers for successful tests
Refrozen ice	DF1, 2, 3, 4, 5, 6, 13, 15, 17, 18, 19, 20, 23, 24, 25, 26, 27, 28, 30
Spray or atmospheric ice	DS1, 5, 13, 15, 16, 21, 22, 23, 25, 26, 27, 28, 29
Compacted frozen snow	DC1, 2, 3, 4, 13, 14, 18, 19, 25, 26, 30, 31

Figure 3.4 shows the variation of  $F_x$  (vertical scraping force or downforce) with ice type and temperature. Ice scraping force increases with decreasing temperature, as would be expected.

As is evident from Figure 3.4, there is significant scatter in the data. This reflects the significant variations in the force traces evidenced by figures 3.1 and 3.3. Such variation is typical of a brittle fracture type of process, and is to be expected under these circumstances. On this basis one might expect the scatter to increase with decreasing temperature, as the ice becomes more brittle. In an absolute sense this is clearly true. The error bars get larger as the temperature decreases.

### Fx as a Function of Temperature

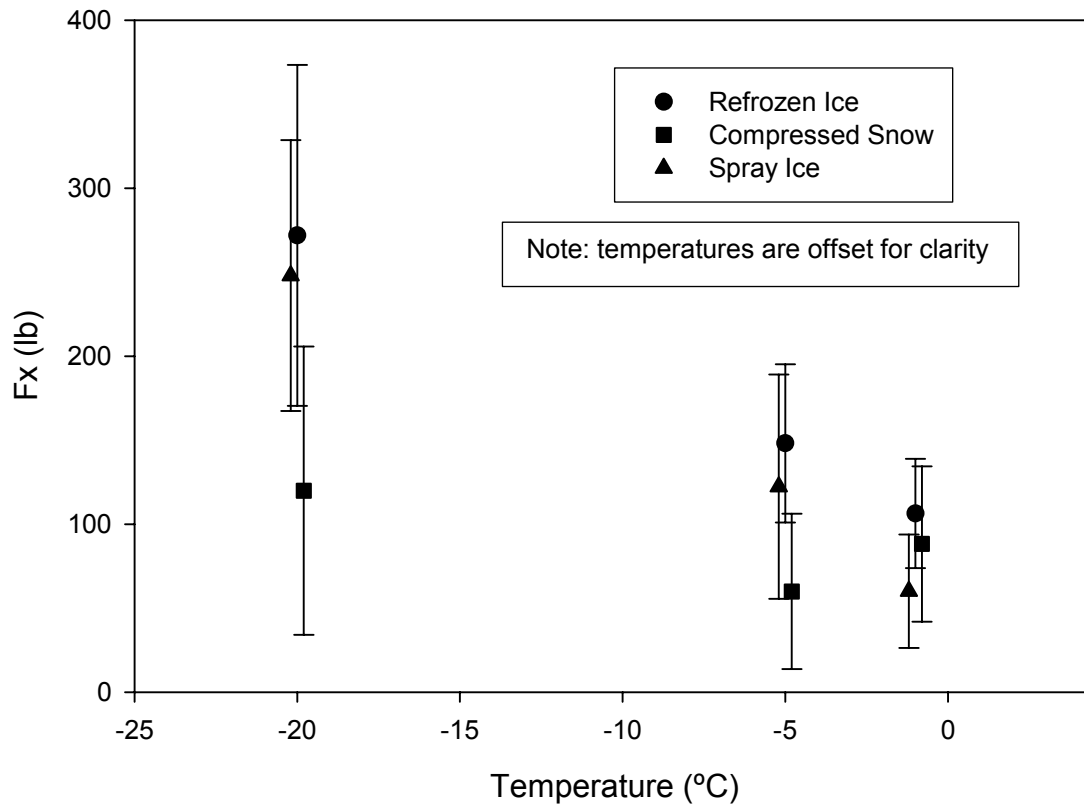


Figure 3.4: Variation of Vertical Force ( $F_x$ ) with Temperature

Figure 3.5 shows the variation of the horizontal scraping force ( $F_z$ ) with temperature for the three ice types. In contrast with the vertical force, there is no significant trend in the scraping force with temperature. Nor does it appear that the scatter increases with decreasing temperature. It is interesting to note that as temperature decreases, the downforce becomes substantially larger than the scraping force. This is further considered in Chapter 4.

### Fz as a Function of Temperature

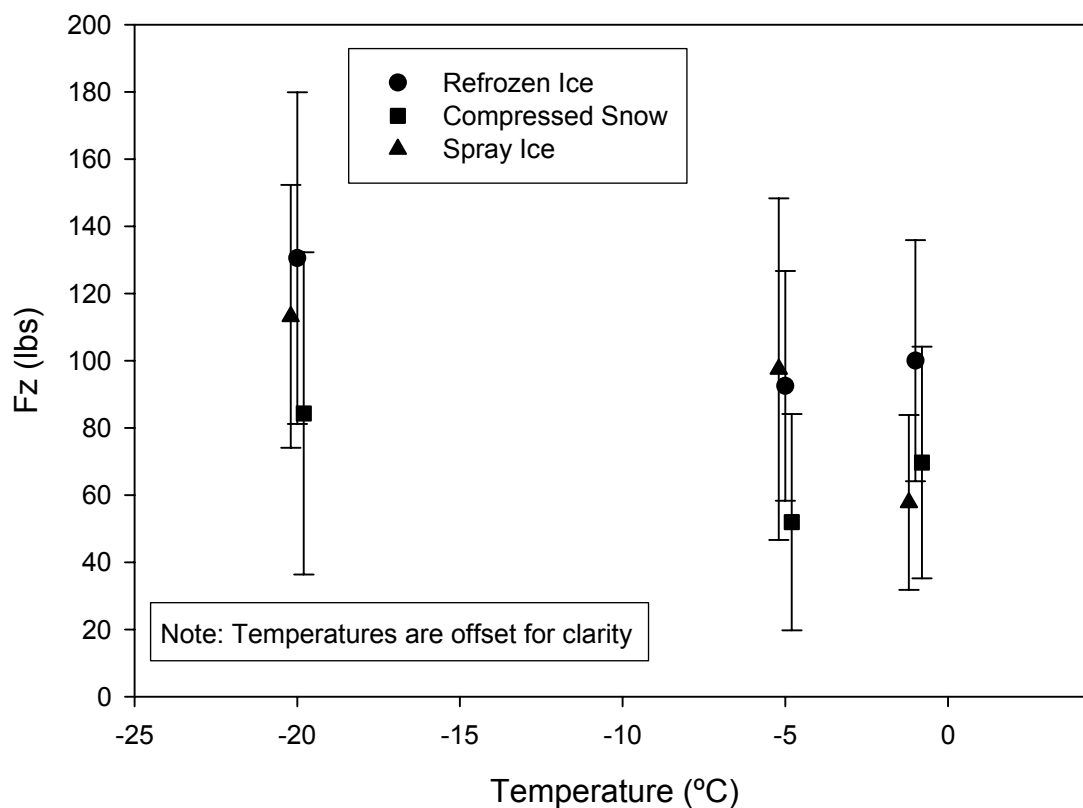


Figure 3.5: Variation of Horizontal Force (Fz) with Temperature

### 3.3 Results from Chemical Tests

In the tests on ice types described in 3.2, the goal was to measure loads when ice had bonded well to the concrete samples. In the tests on chemicals and their effects on scraping loads, the goals were a little different. In this case, the intent was to determine how long it would take the chemical to reduce the scraping load. Thus, a perfectly acceptable result would be a test wherein the loads are not statistically different from zero – this would indicate that the chemical had weakened the bond between the ice and the pavement.

The procedure, as indicated in Chapter 2, was to take an ice-covered specimen and apply chemicals to the ice surface of the specimen. Then, after a certain delay period (between 10 and 40 minutes) the sample would be scraped and the load measured. Three possible outcomes were envisaged. First, as the delay time increased, there might be no change in scraping load until some critical time was reached (basically when the chemical had penetrated to the interface between concrete and ice) at which time the scraping load would fall to zero. The second case, in essence a sub-set of the first, would result in no change at all of scraping load, because the maximum delay time of 40 minutes was insufficient to allow penetration of the ice to the pavement by the chemical. The third case would be if the scraping resistance of the ice were gradually reduced by the penetration of the chemical into the ice, perhaps all the way to zero. As it happens a fourth outcome was observed. In this fourth case, the scraping load increased again after an initial decrease had been observed, perhaps as a result of re-freezing at the ice-pavement interface.

**Table 3.2: Zero-load Responses for Chemical Tests**

Chemical used	Delay Time (minutes)	# of zero-load responses
Calcium Chloride (solid)	10	3
	20	3
	30	0
Sodium Chloride (solid)	10	0
	20	0
	30	2
	40	2
Sodium Chloride (27.3% brine)	10	0
	20	0
	30	2
	40	2

Table 3.2 indicates how many tests under each condition gave a zero-load response, indicating the chemical had destroyed the bond between ice and pavement. As

noted in Chapter 2, three samples were tested under each condition, and all tests were conducted at  $-5^{\circ}\text{C}$ .

The implication of the results in Table 3.2 are that the sodium chloride in both solid and brine form required about 30 minutes to penetrate to the ice-pavement interface in sufficient degree to weaken the bond there. The Calcium Chloride flake penetrated much more rapidly than either the solid Sodium Chloride or the liquid sodium chloride brine. However, after only 30 minutes the Calcium Chloride samples had refrozen firmly to the concrete samples, and were giving horizontal and vertical scraping forces very similar to those for refrozen ice at  $-5^{\circ}\text{C}$ . The load traces for all chemical tests are given in Appendix B.

## CHAPTER 4

### ANALYSIS AND DISCUSSION

#### 4.1 Implications from the Ice Type Tests

As noted above, three different ice types were tested: refrozen ice, spray ice, and compacted snow. Given the nature of the failure (a brittle fragmentation of the ice or compacted snow into many, very small, particles) the high level of scatter is to be expected. The high level of scatter means that care must be taken in interpreting the results. The results suggest similar scraping forces and down-forces for the refrozen and spray ice at both  $-20^{\circ}$  and  $-5^{\circ}$  C. This is consistent with the measurements of their densities (see Table 2.1) which are very close in value. At these two temperatures ( $-20^{\circ}$  and  $-5^{\circ}$  C) the compressed snow required both a lower scraping force and a lower down-force, again, reflecting the lower density of that material as compared with the refrozen ice and the spray ice.

It is worth noting that the values of the forces measured in this series of tests are very close to those found (at the  $-5^{\circ}$  C temperature) in a different test series conducted by Gawronski (see Gawronski, 1994 and Nixon et al. 1996), for the refrozen ice type (which was essentially the ice type tested by Gawronski).

At the warmest test temperature ( $-1^{\circ}$  C) the picture becomes a little more confused. Both the down-force and the scraping force for the spray ice becomes less than that for the compressed snow (although the scatter bands overlap considerably). In spite of the scatter, it appears that at this warmer temperature, the spray ice is weaker (or more easily scraped) than the refrozen ice. It is unlikely that a structural change is occurring in the spray ice that does not occur in the refrozen ice. Rather, it is possible that the method of making the spray ice for the high temperature tests may have weakened the spray ice. At  $-1^{\circ}$  C the spray ice would not freeze properly so it was formed at  $-5^{\circ}$  C and then allowed to equilibrate to the test temperature. It is possible that this change in temperature from formation to test condition gave rise to some interfacial stresses between ice and pavement that served to weaken the ice and thus reduce its resistance to scraping (as measured by scraping force and down-force). This might explain why the spray ice becomes much easier to scrape than the refrozen ice at  $-1^{\circ}$  C, but clearly,

additional work would be needed to clarify this point, and such work is beyond the scope of this study.

It is also worth noting that at the lowest test temperature ( $-20^{\circ}\text{C}$ ), the scraping or horizontal force became much less than the vertical or down-force. This is shown in Figure 4.1 which plots the ratio of the vertical and horizontal forces as a function of temperature.

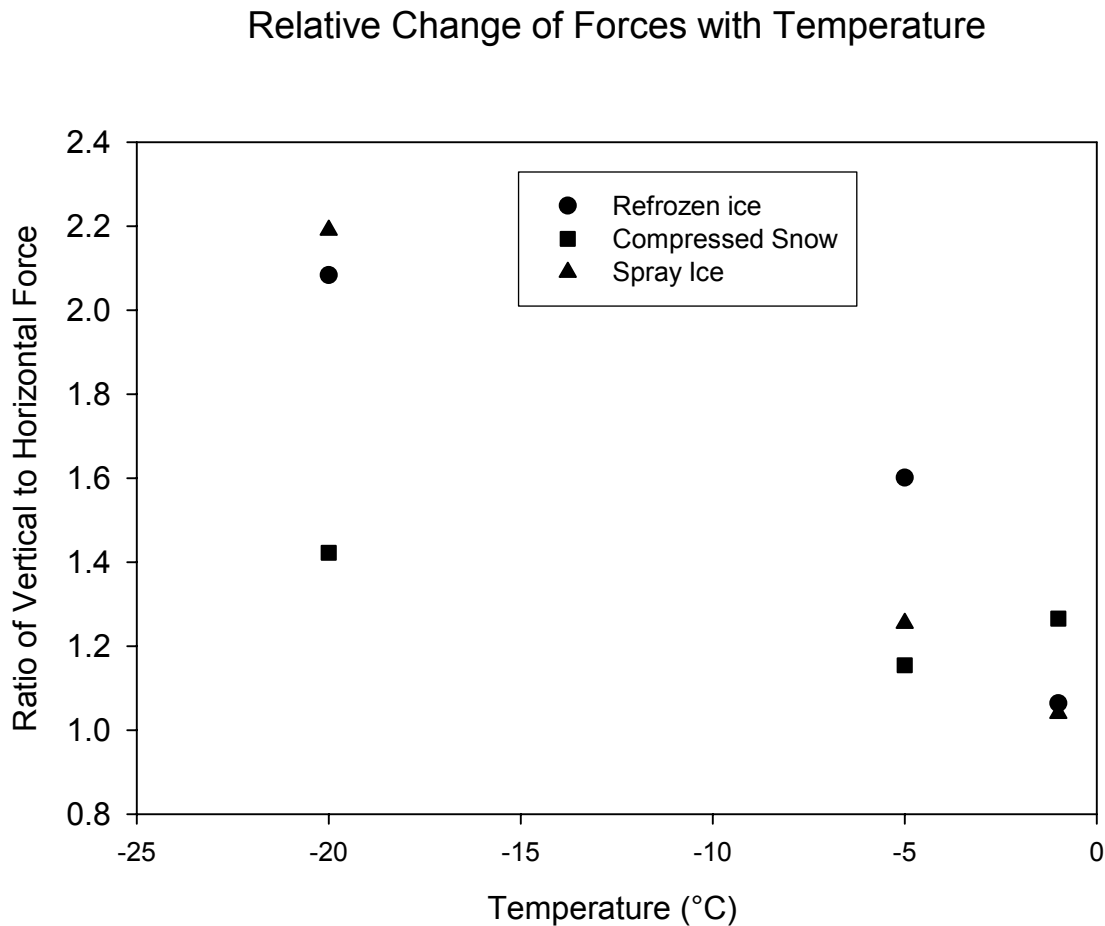


Figure 4.1: Variation of the Ratio of Vertical to Horizontal Forces with Temperature

This trend is most noticeable for the refrozen and spray ice types, being hardly present for the compressed snow. It may relate to the process whereby the ice is disaggregated as it is scraped. It has been noted elsewhere (Nixon et al., 1996) that when



ice is scraped, the ice itself is broken into many small pieces, some of which must then be re-compressed to “squeeze” under the cutting edge. The more re-compression is needed, the higher the down-force or vertical force will be, relative to the horizontal or scraping force. It might be expected, therefore, that the compressed snow, having a lower density than the refrozen ice and spray ice, would exhibit a lower ratio than those other two ice types, and that is certainly the case at lower temperatures. This would suggest that the model of failure described by Nixon et al. (1996) holds well when brittle failure occurs, but at very warm temperatures (in this study, at  $-1^{\circ}\text{C}$ ) the ice failure is not solely by brittle disaggregation.

The operational implications of Figure 4.1 are rather profound. The figure shows that spray ice and refrozen ice will become increasingly difficult to remove with, for example, an underbody plow, as temperature decreases (see Nixon et al., 1993; Nixon and Potter, 1996). The obvious operational implication is that ice on the highway should be treated as soon as possible after it forms, rather than returning to it after a storm is over, when temperatures may well fall rather rapidly.

#### **4.2 Implications from the Chemical Tests**

As discussed in Chapter 3, three types of behavior were noted when chemical was applied to samples prior to their being scraped. One exhibited behavior was that the scraping force was essentially unchanged from that seen when no chemicals were used. A second type of behavior was that the force needed to scrape the samples dropped to zero. A third type of behavior, which was unexpected prior to testing, was that after a longer period of time, the ice would refreeze to the concrete surface.

The refreezing behavior is of course well known operationally. It is interesting to compare the refrozen bond strength with that of ice not chemically treated. From the three samples treated with Calcium Chloride and allowed to “sit” for 30 minutes after chemical application (i.e. the chemically treated samples that exhibited refreeze behavior) the means and standard deviation for the horizontal (scraping) and vertical (down-force) loads were  $72.9 \pm 34.2$  lbs and  $229 \pm 106$  lbs respectively. This compares with the strengths observed for untreated ice (refrozen at  $-5^{\circ}\text{C}$ ) of  $92.5 \pm 34.2$  lbs and  $148 \pm 47.2$  lbs respectively. Statistically, the two populations cannot be distinguished one from the

other. Again, the operational implications are clear. If ice is treated with chemicals and not rapidly removed mechanically from the road, it will refreeze with a bond strength equal to that before chemical treatment. Thus, after applying chemicals, the road must be plowed to remove the melted and melting snow and ice.

For two of the three chemical applications (solid sodium chloride, and sodium chloride in a 27.3% brine solution) the samples exhibited statistically significant non-zero scraping forces in all cases, for 10 and 20 minutes after application. Even after 30 and 40 minutes, at least one sample under each condition exhibited non-zero scraping forces. Figure 4.2 shows how the average horizontal force changes with delay time.

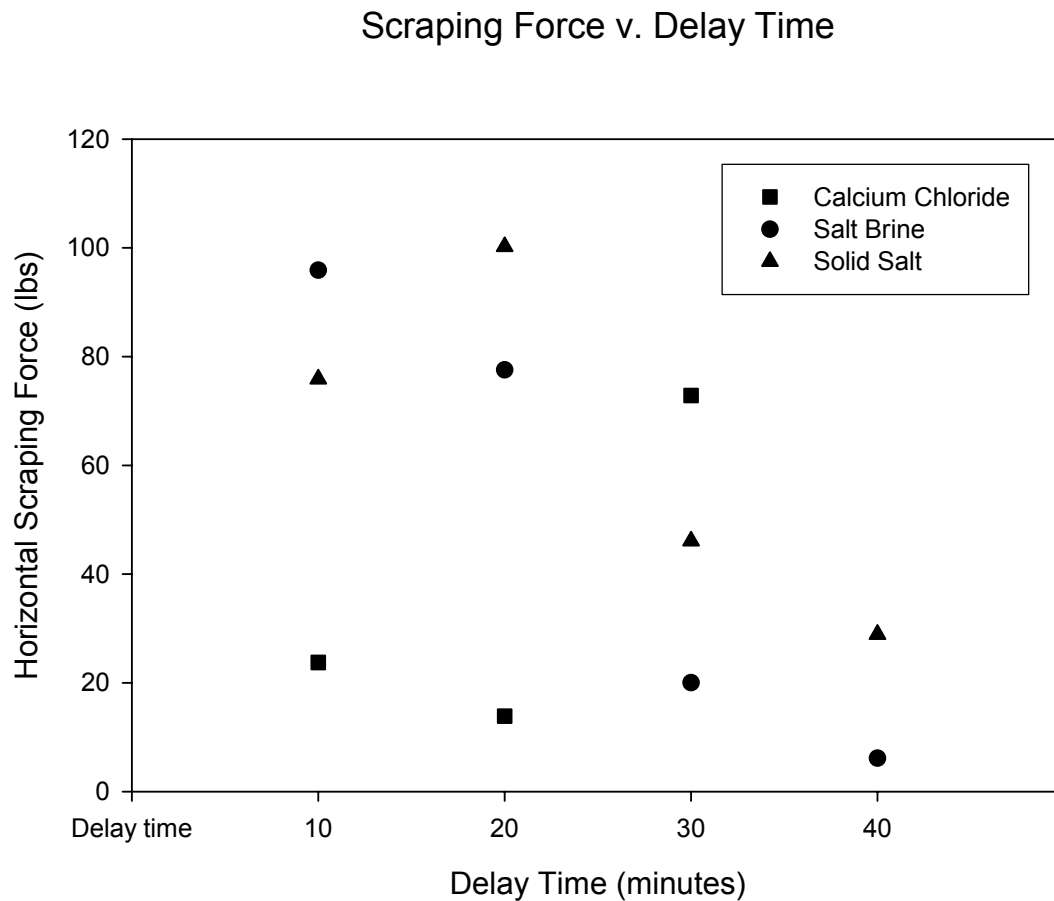


Figure 4.2: Horizontal Scraping Force as a Function of Delay Time

The implications from these results are clear. First, it takes sodium chloride (whether solid or as a brine) longer to break the bond at the interface between ice and

pavement than it does calcium chloride. Second, calcium chloride, while acting more quickly, is therefore also more prone to refreeze. The operational implications of this are clear. Calcium chloride is excellent at breaking the bond quickly but if used, care must be taken to avoid refreezing. Sodium chloride acts less quickly and is thus less prone to refreezing.

## **CHAPTER 5**

### **CONCLUSIONS**

A series of tests have been conducted on three different ice types (refrozen ice, atmospheric ice and compressed snow) at three different temperatures ( $-1^{\circ}$ ,  $-5^{\circ}$ , and  $-20^{\circ}\text{C}$ ) to measure the horizontal and vertical forces required to remove the ice types from pavement surfaces. A second series of tests examined the effects on the scraping forces of various chemicals (solid pellets of calcium chloride, solid sodium chloride, and a brine of sodium chloride), when those chemicals were applied to the surface of the ice layer.

The results of these tests indicated that of the three ice types, the compressed snow was the easiest to scrape, while the refrozen ice, in general, required the greatest effort. The also indicated that scraping forces increased significantly for all three ice types as temperature decreased.

The results of the chemical tests showed that the calcium chloride acted within ten minutes to break the bond between ice and pavement essentially completely. However, the same series of tests (using calcium chloride) showed that refreeze would occur within 30 minutes of the original application. Both solid and liquid (brine) applications of sodium chloride showed a breaking of the bond between 20 and 30 minutes after initial application, with no refreeze being observed for the longest test duration (conducted 40 minutes after chemical application).

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## **APPENDIX A**

### Individual Test Results for Ice Type Testing

Note: for each test, the following information is provided:

- Was the test successful (i.e. statistically different from a zero load, both vertically and horizontally)?
- What was the ice type?
- What was the test temperature?
- What was the average and standard deviation for the horizontal force?
- What was the average and standard deviation for the vertical force?

## DF-01

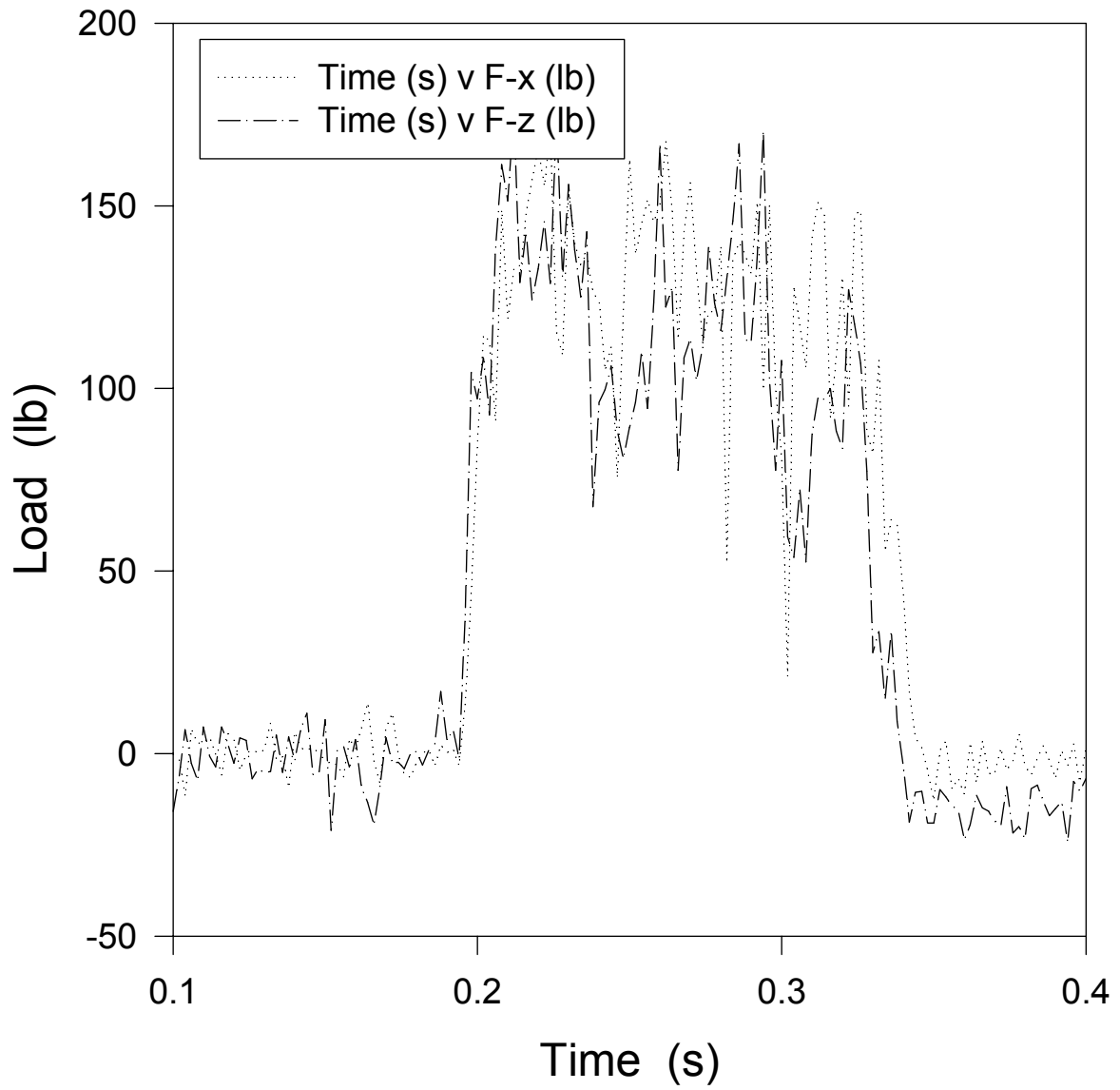


Figure A1: Sample DF-01 Load Trace

Test: Successful

Ice Type: Refrozen

Test temperature: -1° C

Horizontal Force:  $107 \pm 37$  lbs

Vertical Force:  $120 \pm 34$  lbs

## DF-02

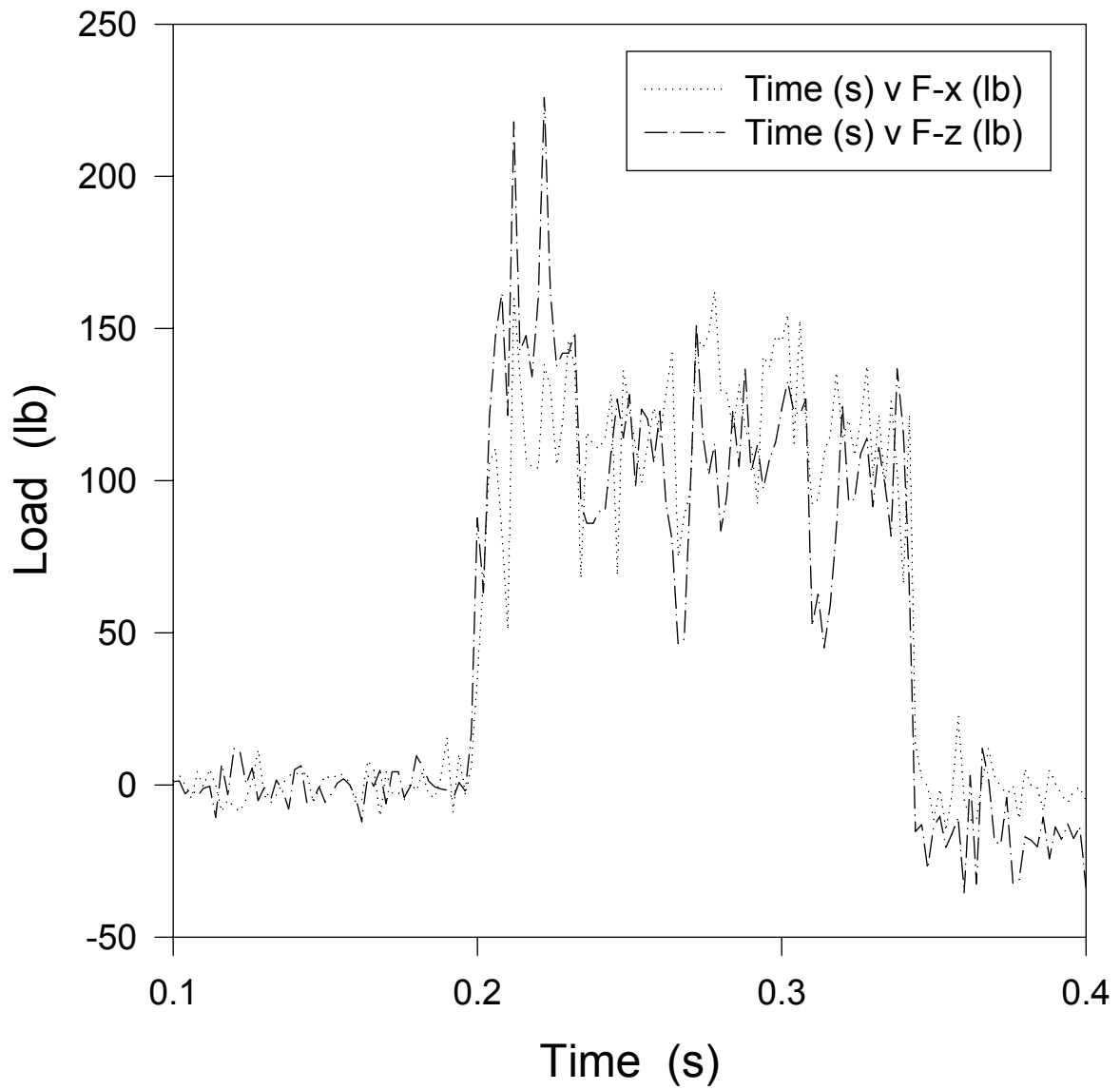


Figure A2: Sample DF-02 Load Trace  
Test: Successful  
Ice Type: Refrozen  
Test temperature:  $-1^{\circ}\text{C}$   
Horizontal Force:  $109 \pm 37$  lbs  
Vertical Force:  $113 \pm 31$  lbs



## DF-03

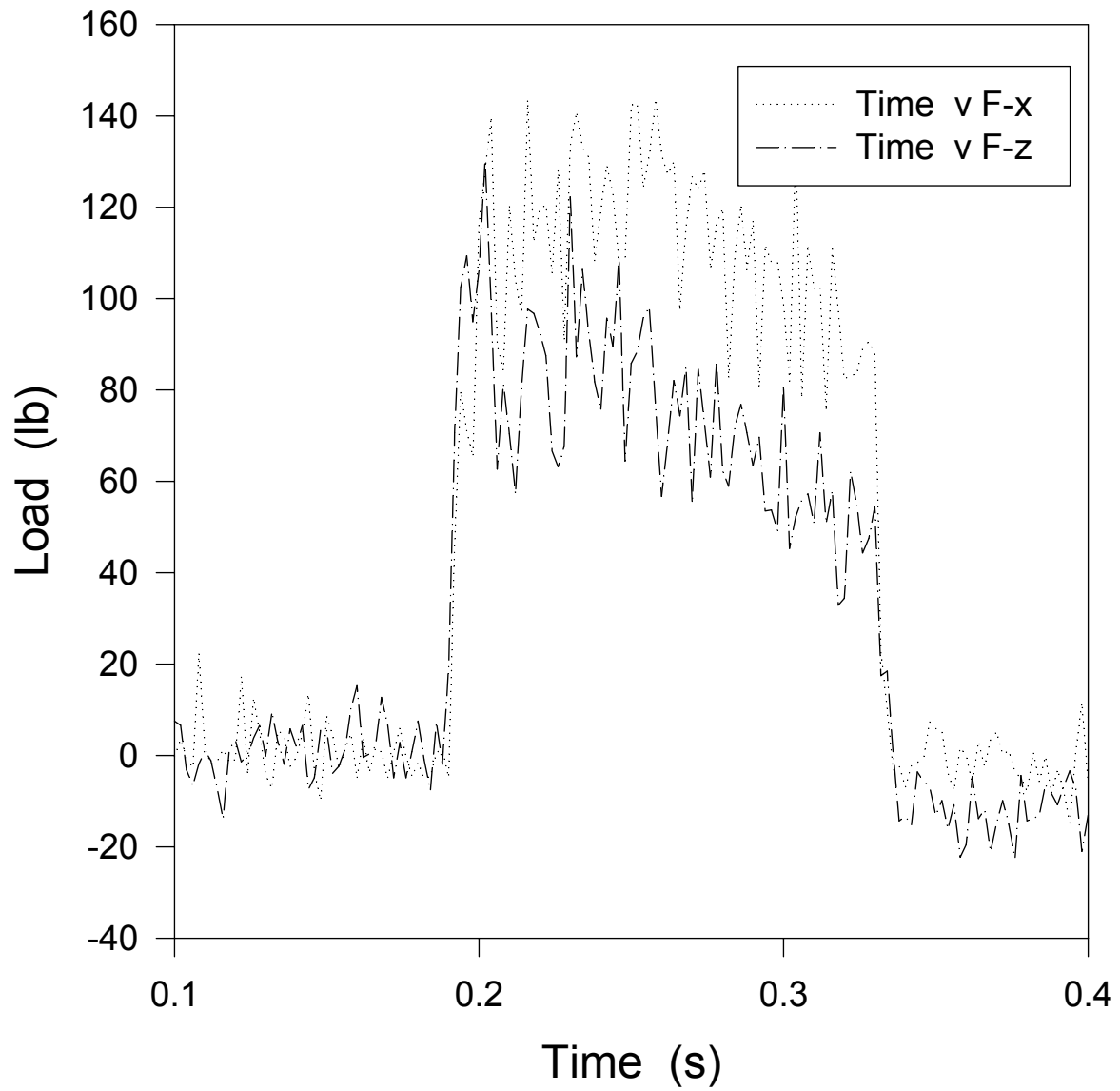


Figure A3: Sample DF-03 Load Trace  
Test: Successful  
Ice Type: Refrozen  
Test temperature:  $-1^{\circ}\text{C}$   
Horizontal Force:  $70 \pm 26$  lbs  
Vertical Force:  $102 \pm 33$  lbs

## DF-04

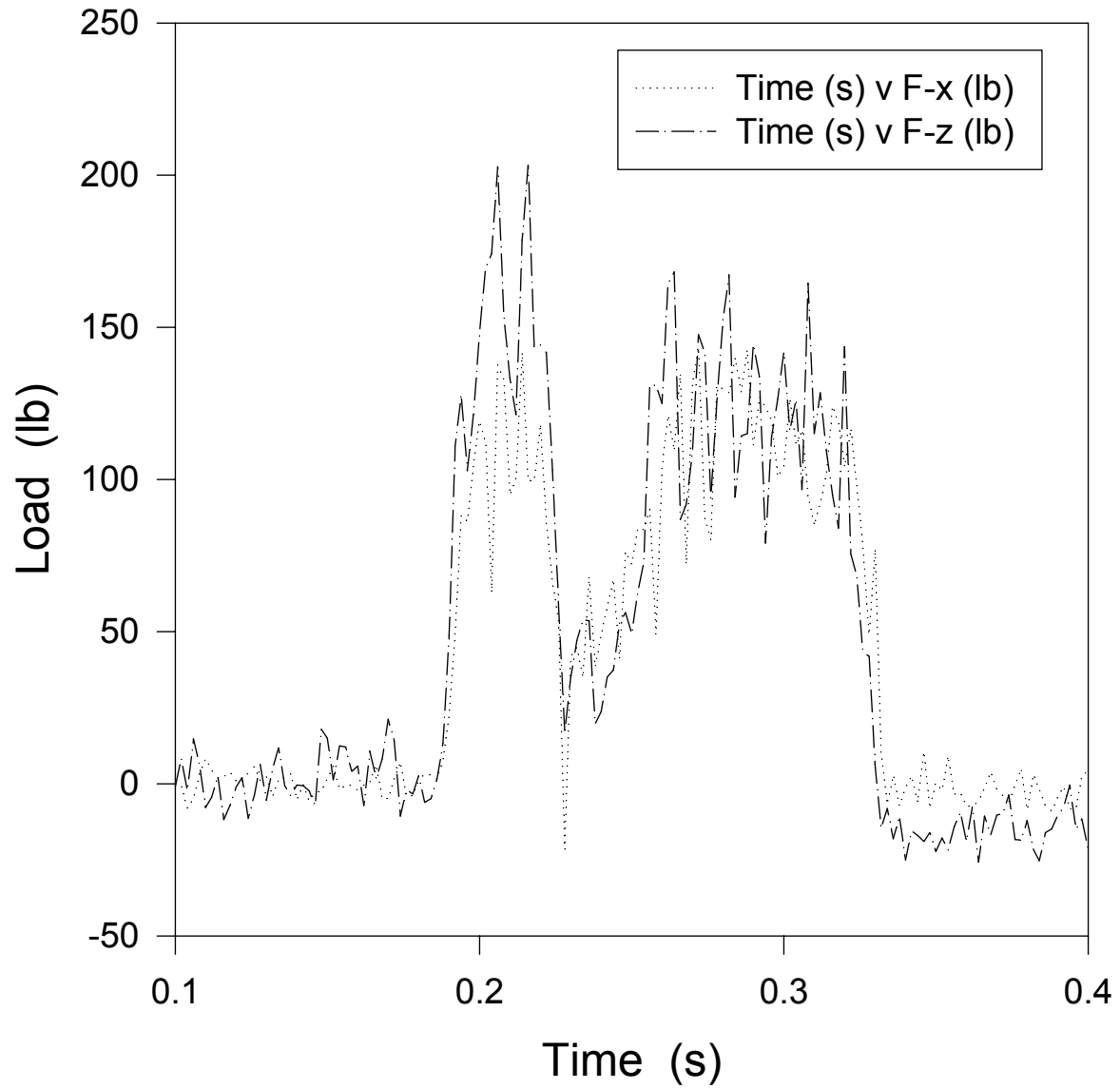


Figure A4: Sample DF-04 Load Trace  
Test: Successful  
Ice Type: Refrozen  
Test temperature:  $-1^{\circ}\text{C}$   
Horizontal Force:  $105 \pm 48$  lbs  
Vertical Force:  $92 \pm 35$  lbs

## DF-05

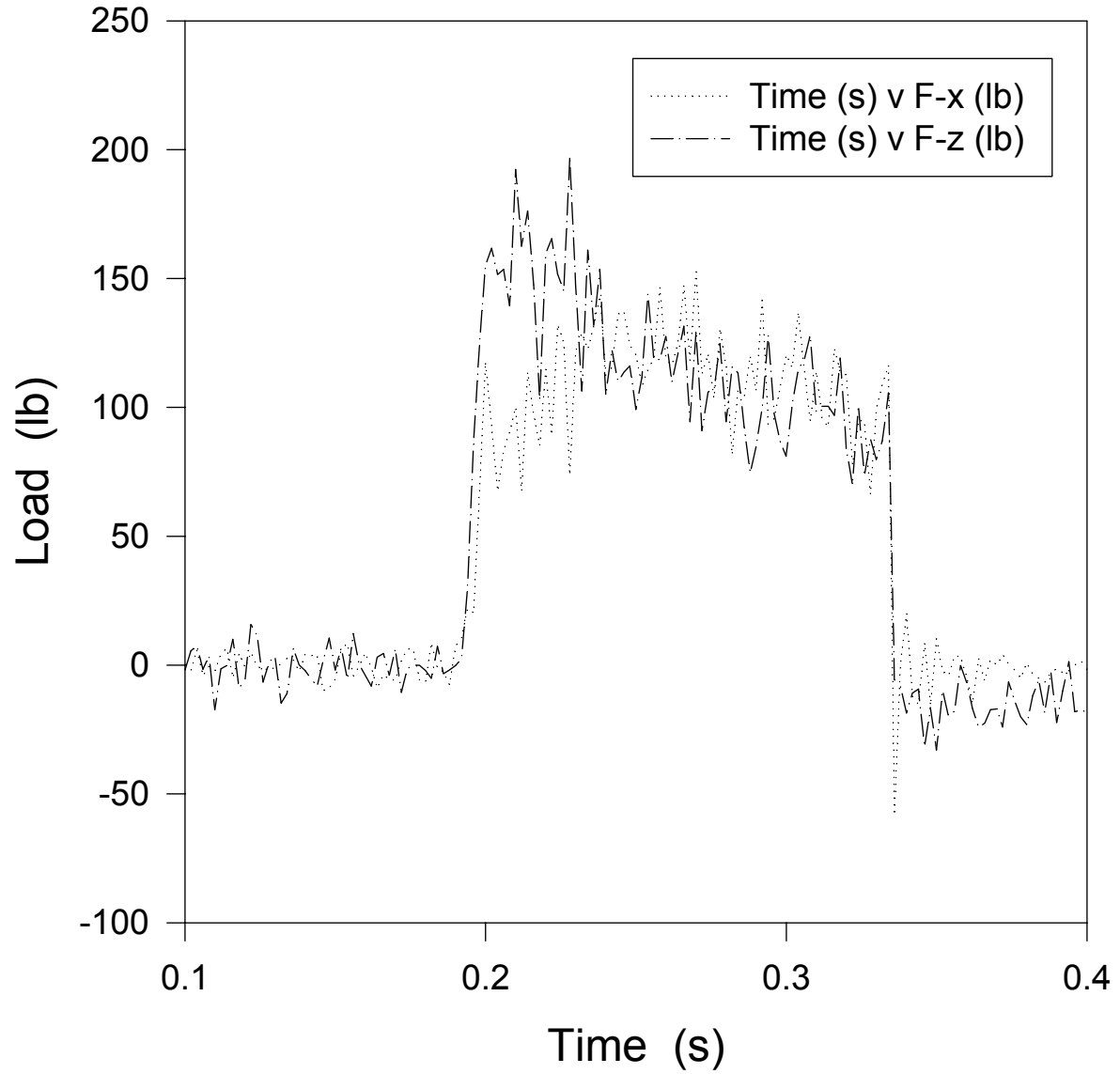


Figure A5: Sample DF-05 Load Trace  
Test: Successful  
Ice Type: Refrozen  
Test temperature:  $-1^{\circ}\text{C}$   
Horizontal Force:  $116 \pm 33$  lbs  
Vertical Force:  $106 \pm 27$  lbs

## DF-06

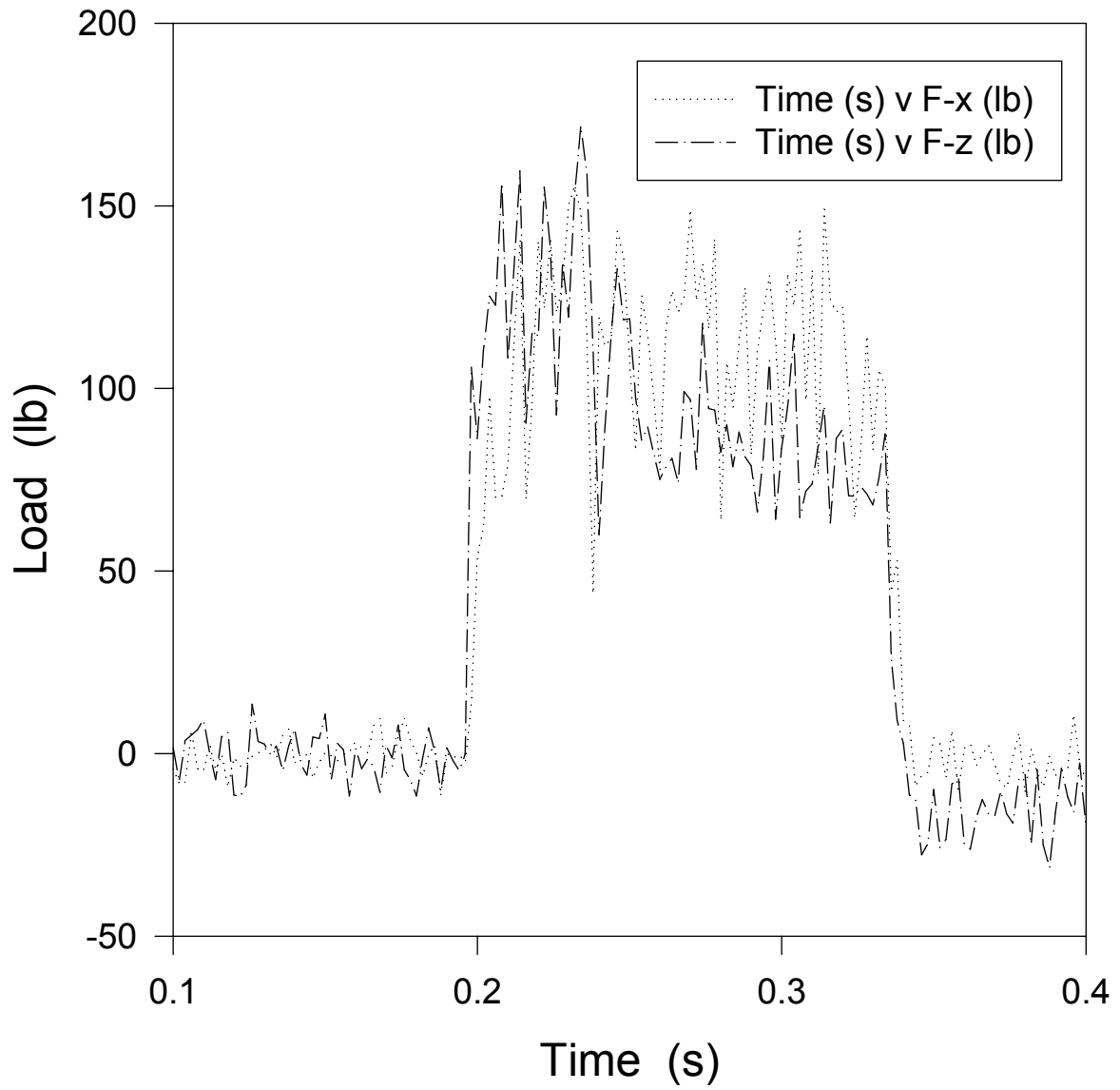


Figure A6: Sample DF-06 Load Trace

Test: Successful

Ice Type: Refrozen

Test temperature:  $-1^{\circ}\text{C}$

Horizontal Force:  $94 \pm 33$  lbs

Vertical Force:  $105 \pm 34$  lbs

## DF-13

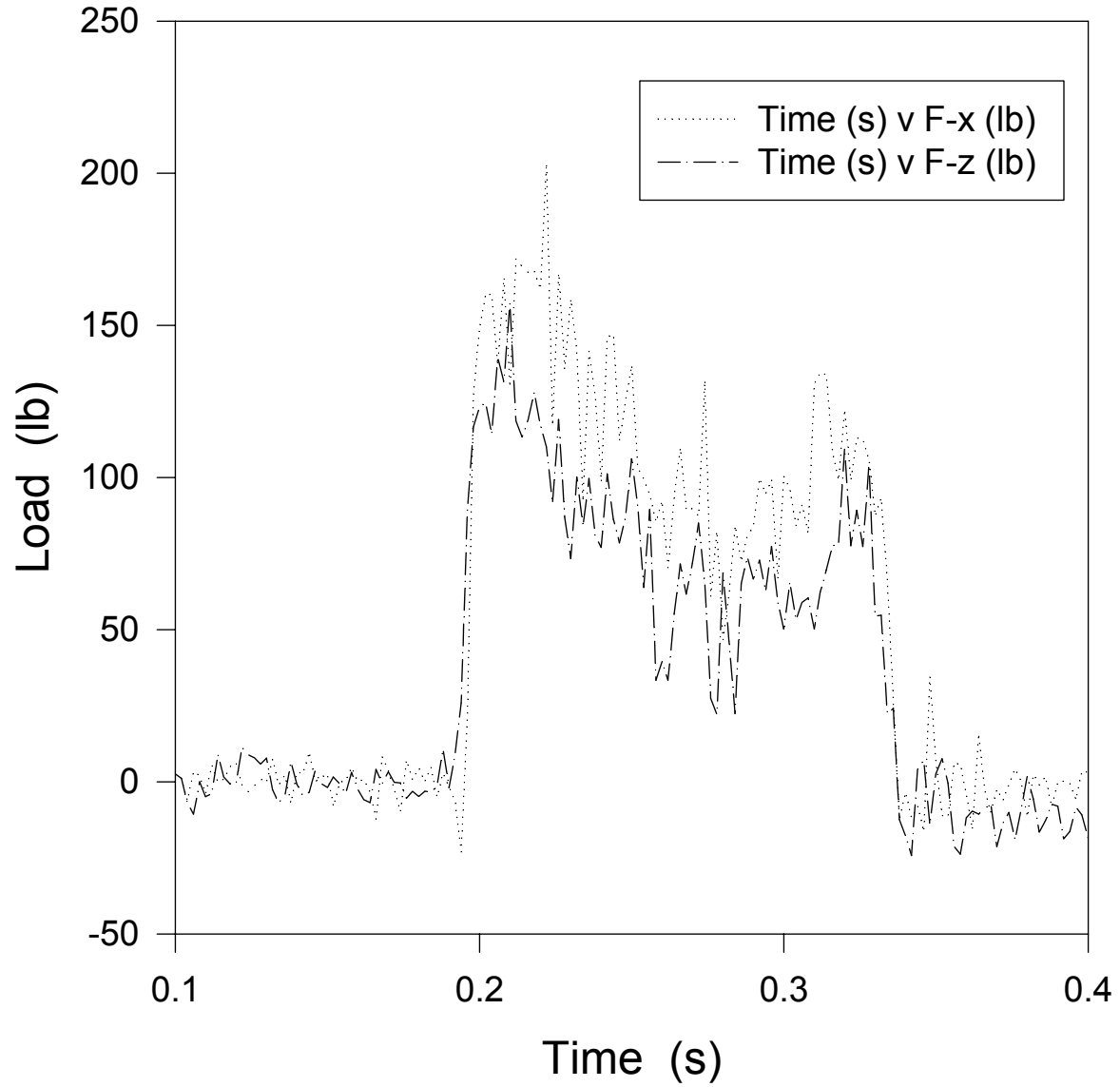


Figure A7: Sample DF-13 Load Trace

Test: Successful

Ice Type: Refrozen

Test temperature:  $-5^{\circ}\text{C}$

Horizontal Force:  $78 \pm 32$  lbs

Vertical Force:  $108 \pm 41$  lbs

## DF-15

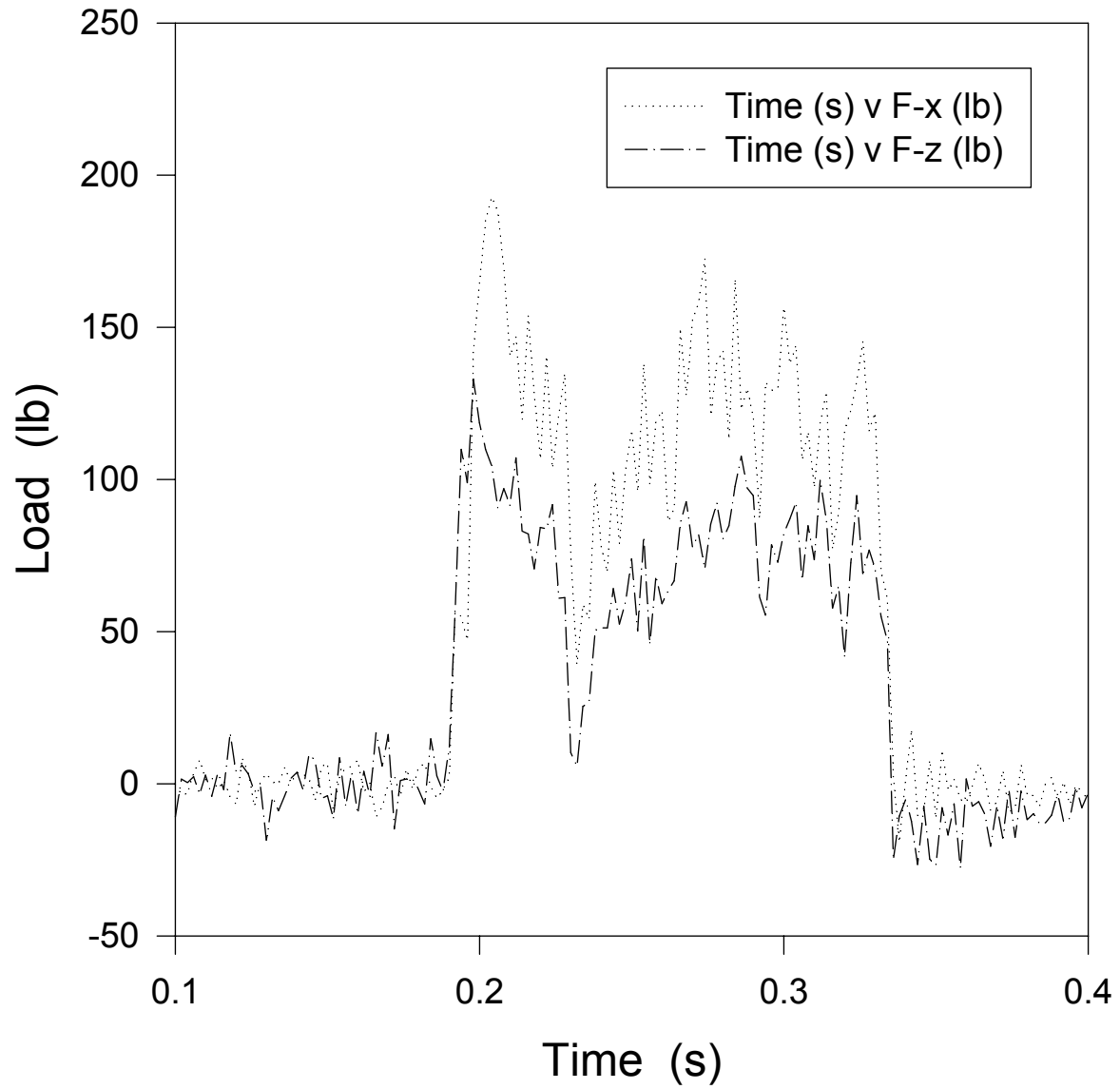


Figure A8: Sample DF-15 Load Trace

Test: Successful

Ice Type: Refrozen

Test temperature: -5° C

Horizontal Force:  $74 \pm 25$  lbs

Vertical Force:  $116 \pm 37$  lbs

## DF-16

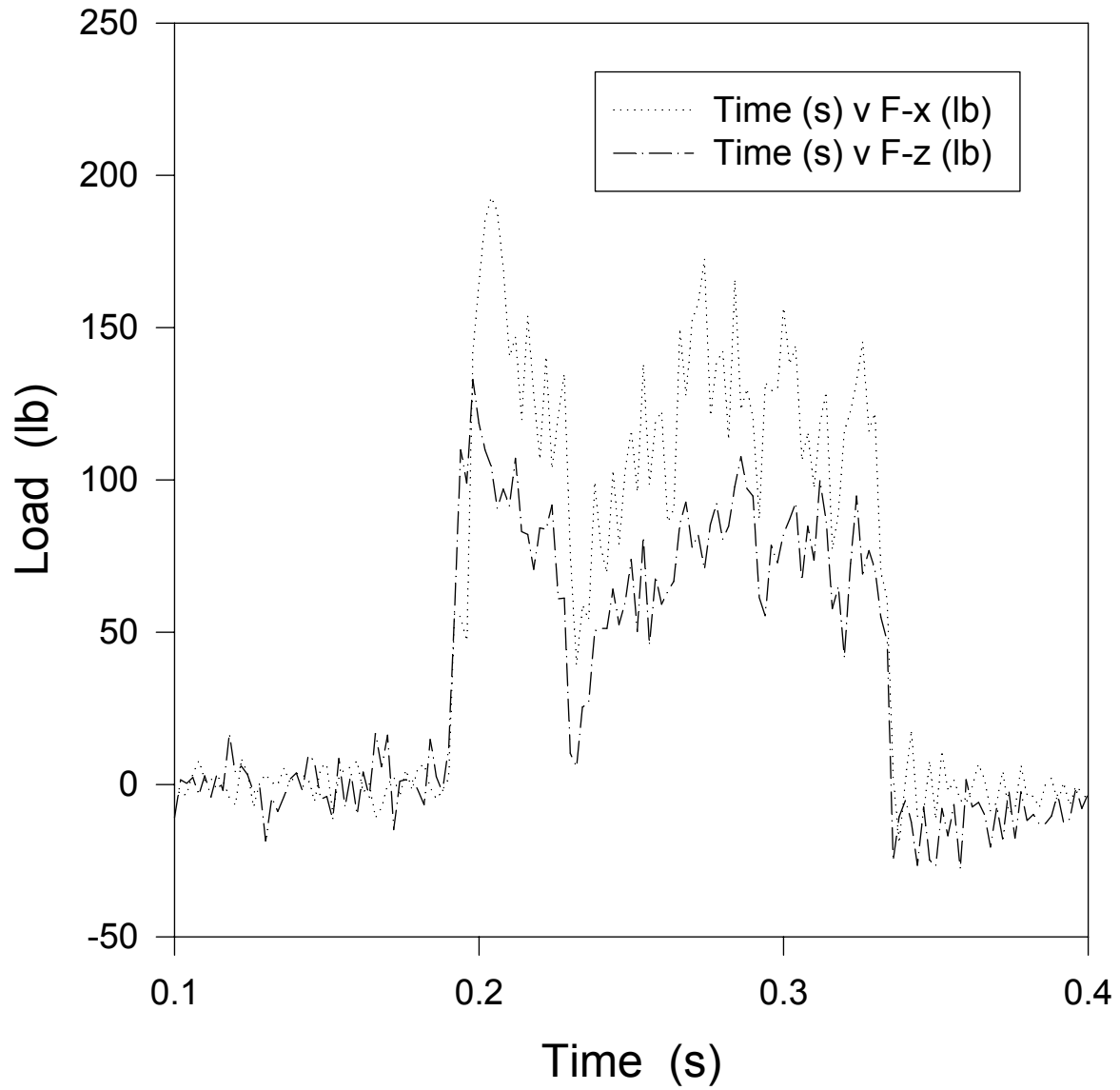


Figure A9: Sample DF-16 Load Trace

Test: Successful

Ice Type: Refrozen

Test temperature:  $-5^{\circ}\text{C}$

Horizontal Force:  $75 \pm 24$  lbs

Vertical Force:  $118 \pm 35$  lbs

## DF-17

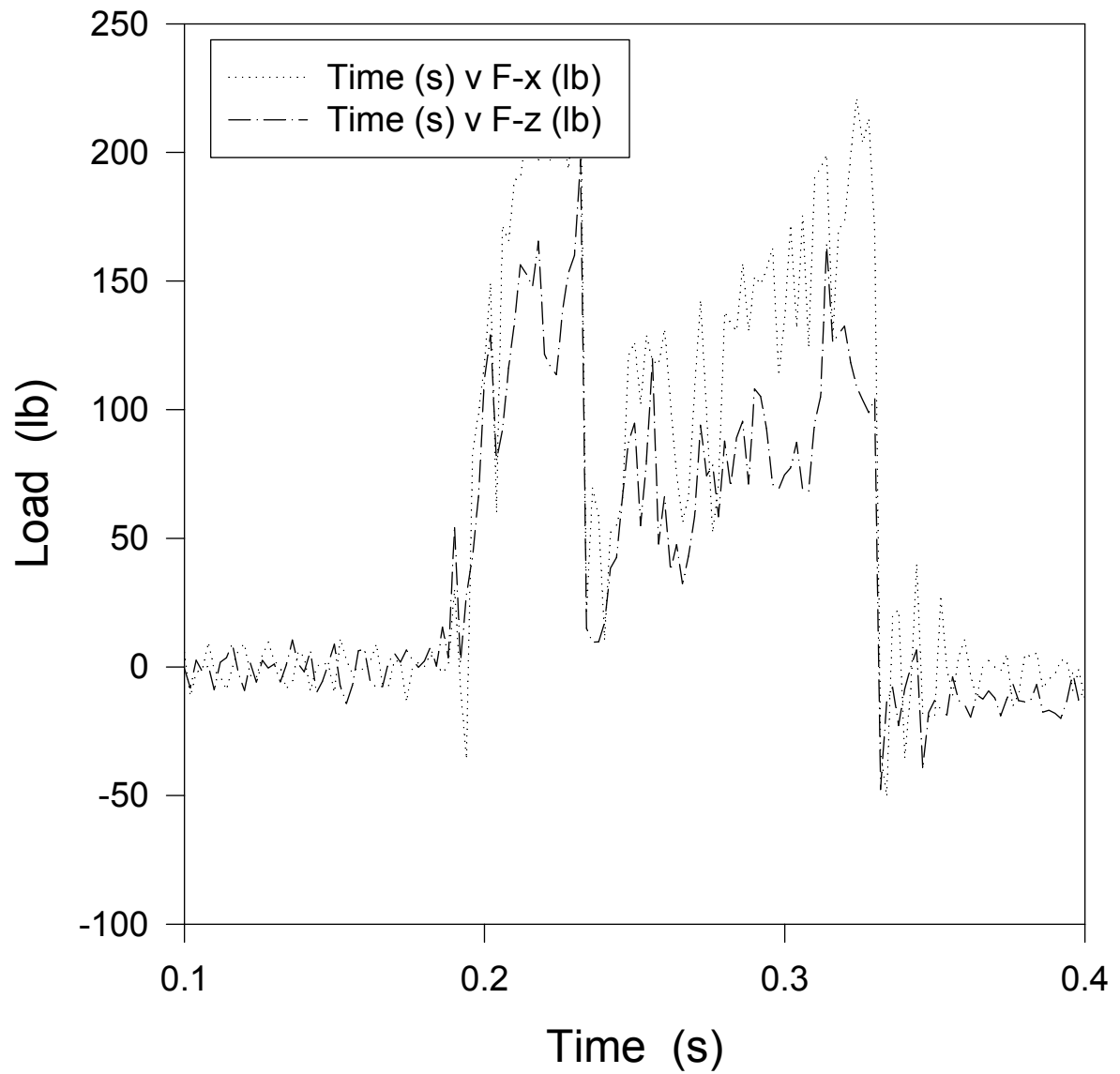


Figure A10: Sample DF-17 Load Trace  
Test: Successful  
Ice Type: Refrozen  
Test temperature:  $-5^{\circ}\text{C}$   
Horizontal Force:  $83 \pm 46$  lbs  
Vertical Force:  $125 \pm 68$  lbs



## DF-18

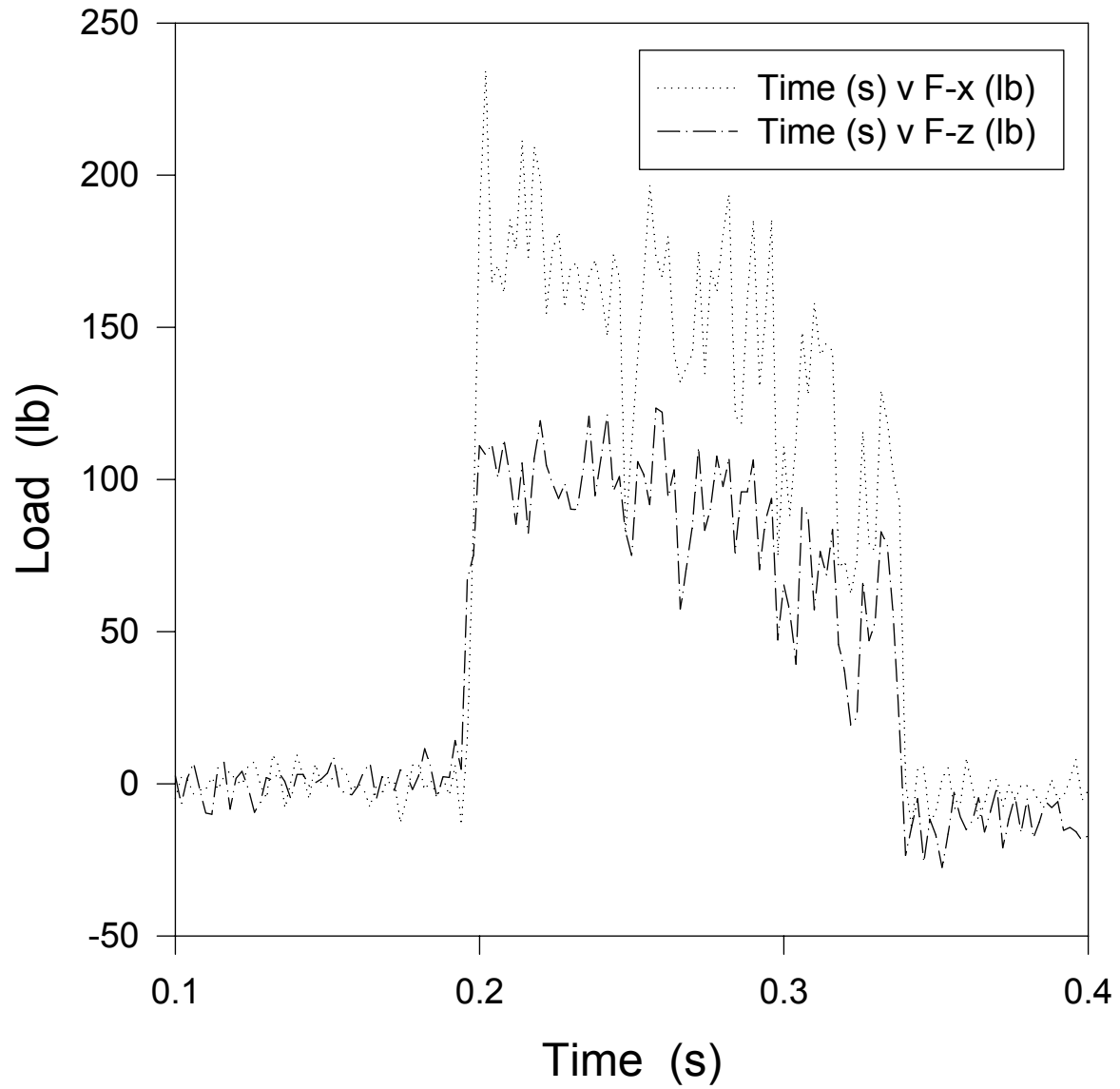


Figure A11: Sample DF-18 Load Trace

Test: Successful

Ice Type: Refrozen

Test temperature:  $-5^{\circ}\text{C}$

Horizontal Force:  $83 \pm 28$  lbs

Vertical Force:  $140 \pm 48$  lbs

## DF-19

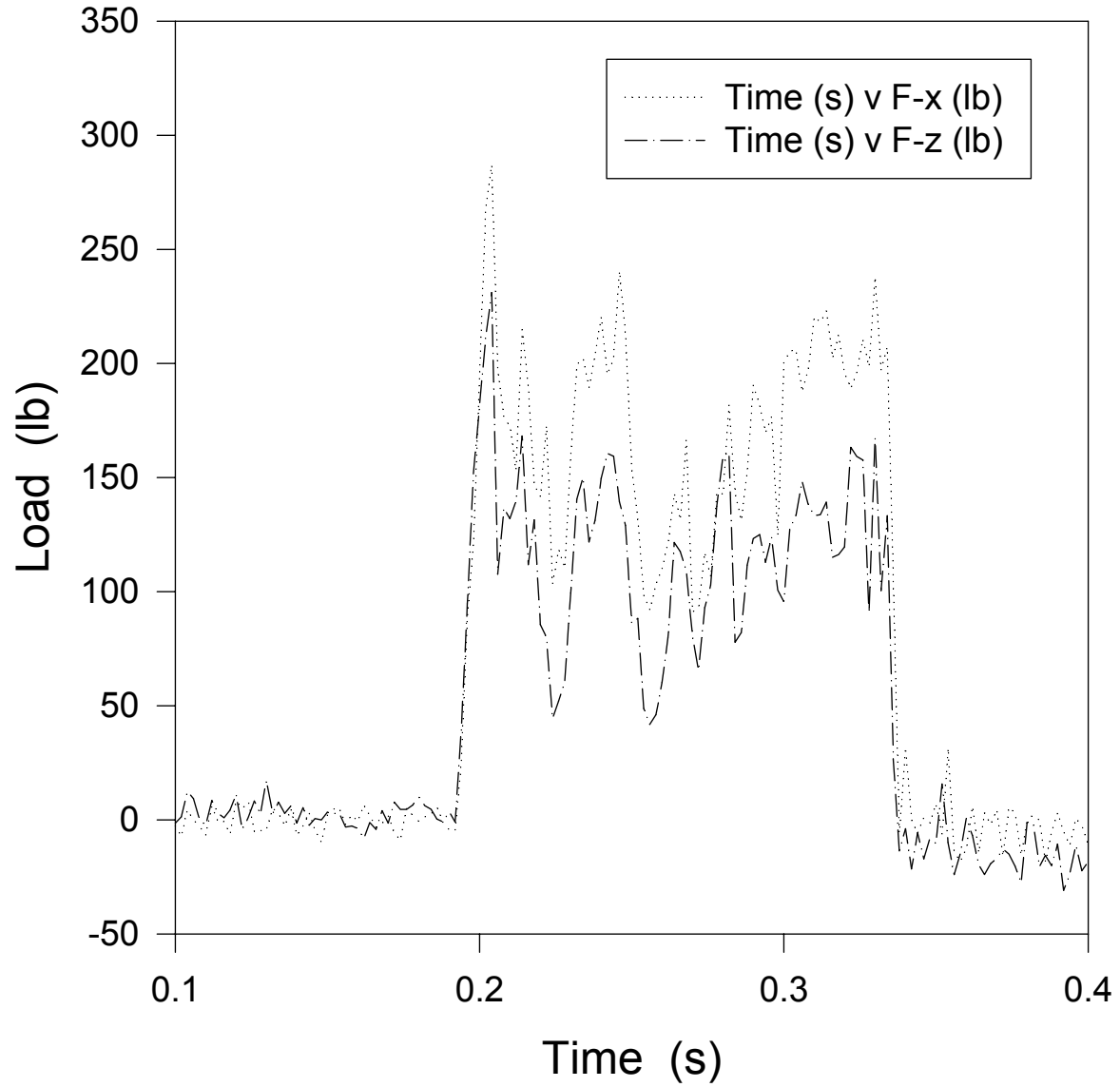


Figure A12: Sample DF-19 Load Trace

Test: Successful

Ice Type: Refrozen

Test temperature: -5° C

Horizontal Force:  $117 \pm 40$  lbs

Vertical Force:  $168 \pm 48$  lbs

## DF-20

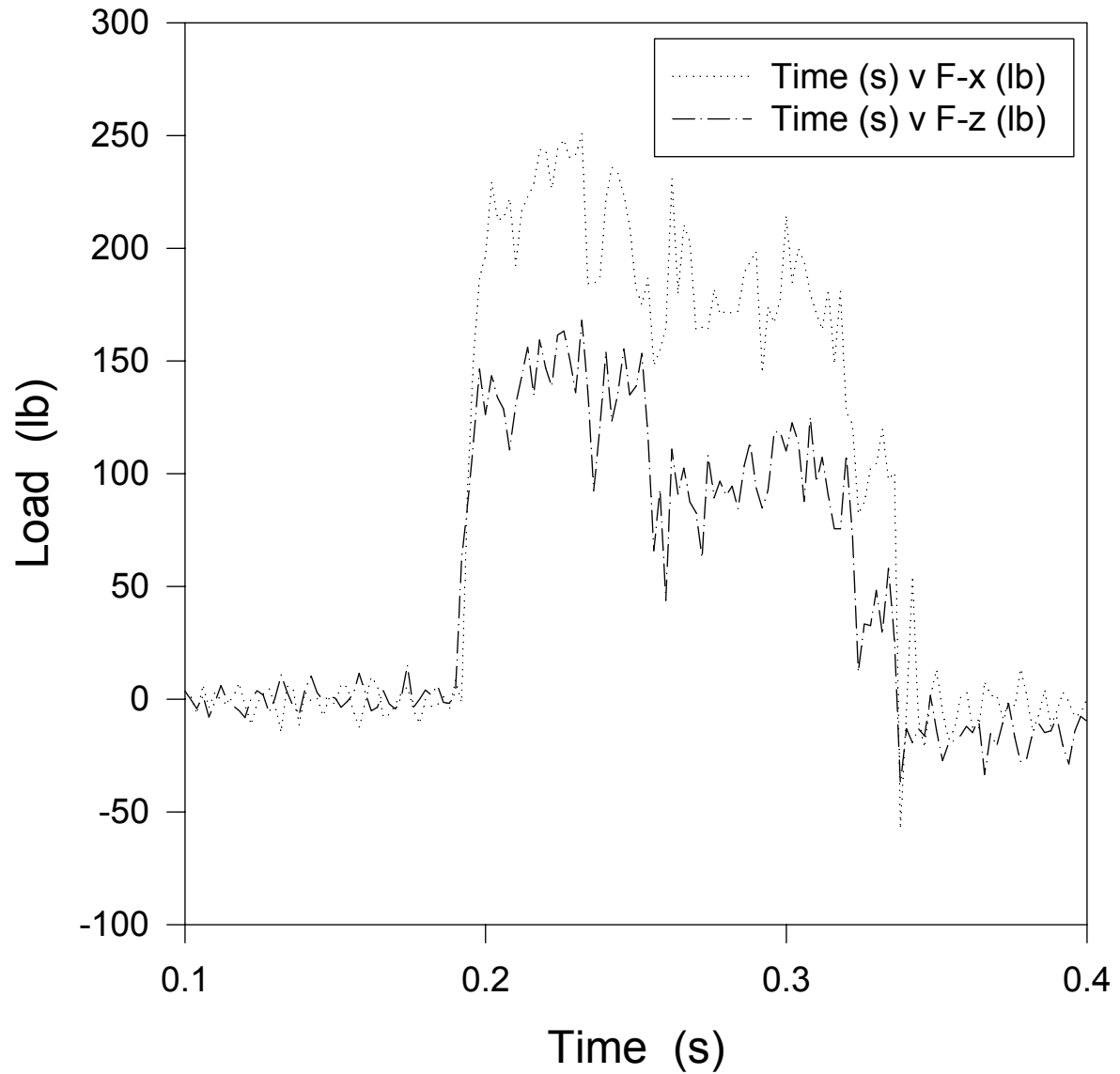


Figure A13: Sample DF-20 Load Trace

Test: Successful

Ice Type: Refrozen

Test temperature: -5° C

Horizontal Force:  $106 \pm 36$  lbs

Vertical Force:  $181 \pm 47$  lbs

## DF-23

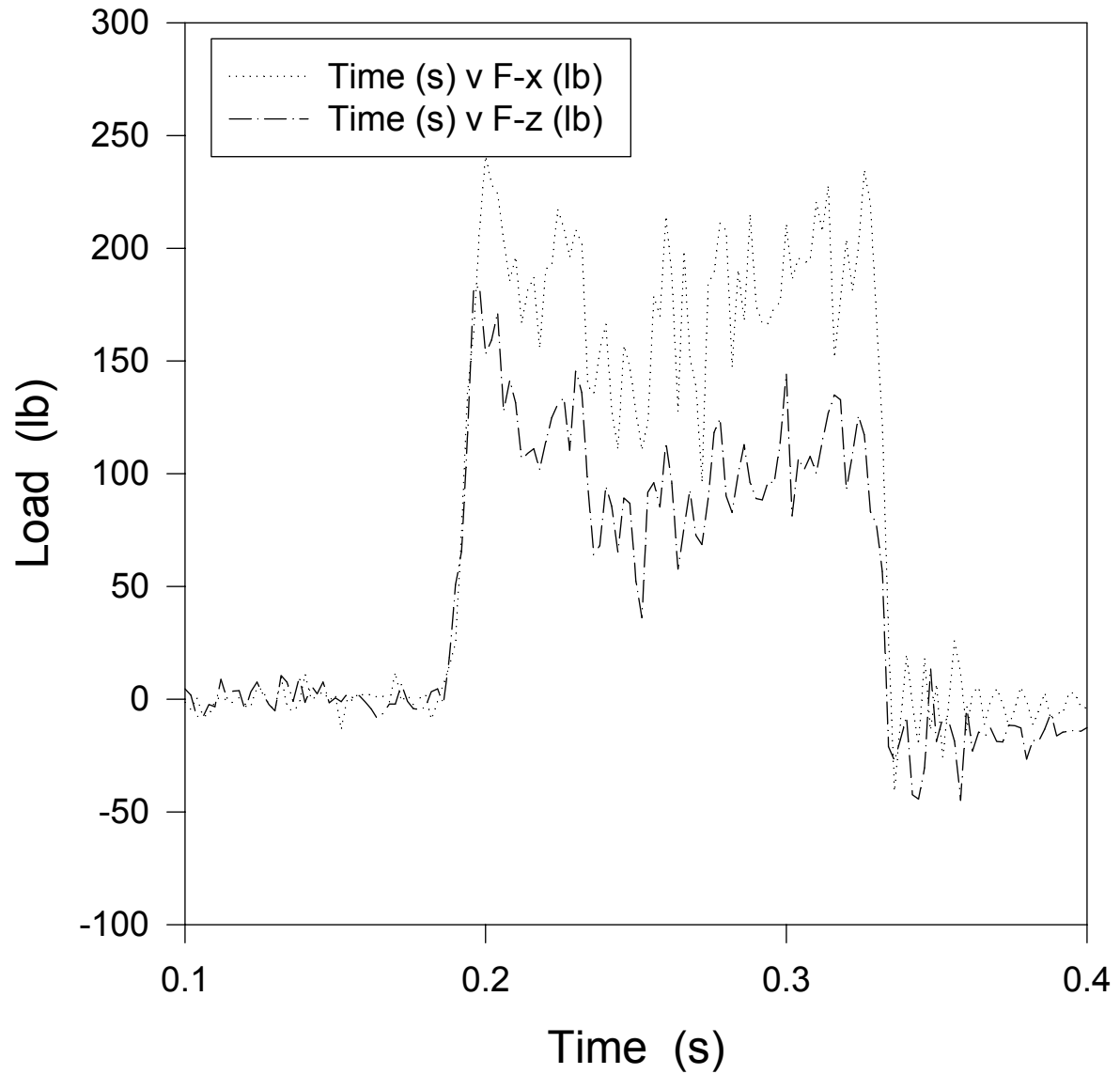


Figure A14: Sample DF-23 Load Trace

Test: Successful

Ice Type: Refrozen

Test temperature: -5° C

Horizontal Force:  $103 \pm 32$  lbs

Vertical Force:  $173 \pm 44$  lbs

## DF-24

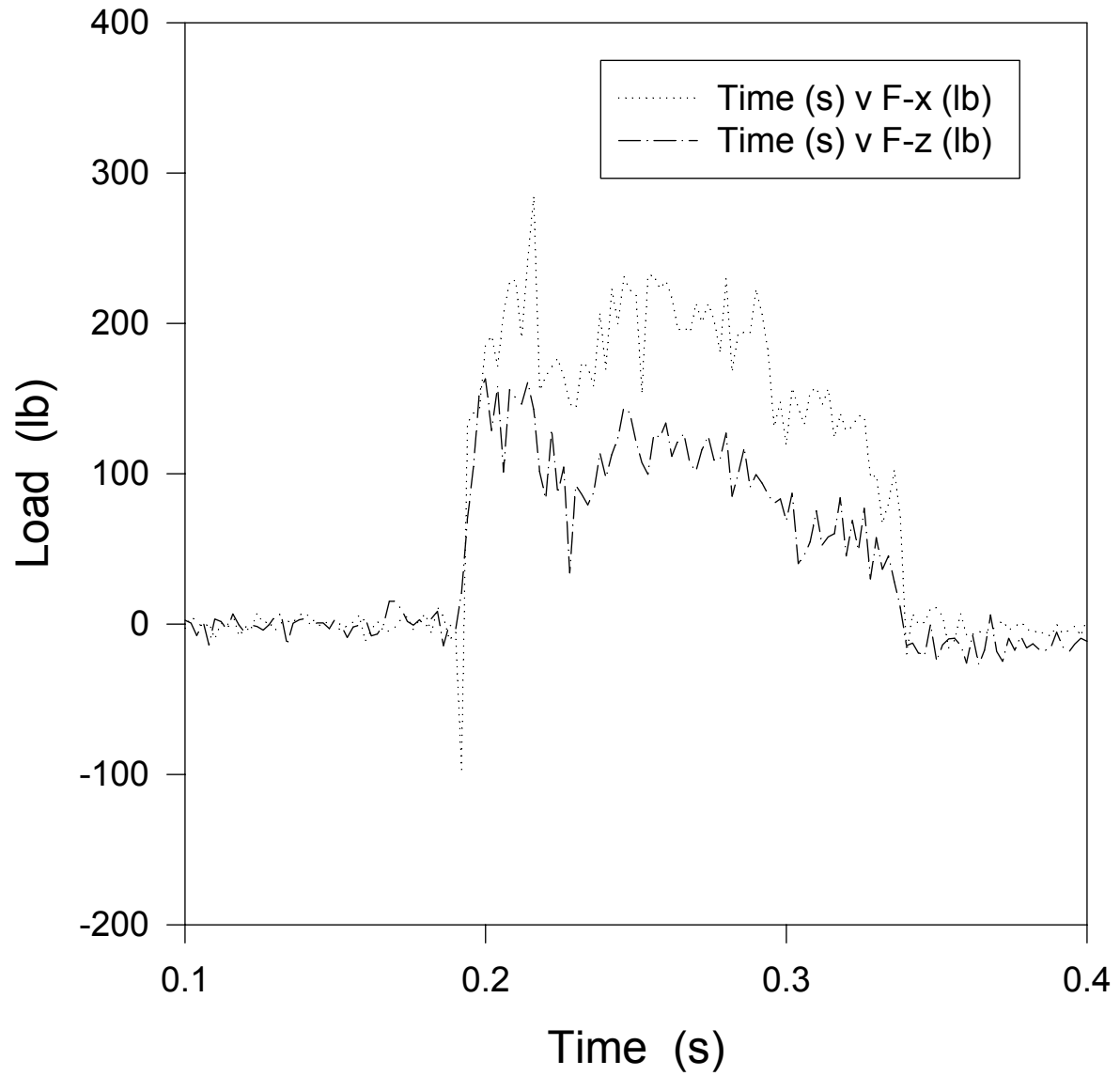


Figure A15: Sample DF-24 Load Trace

Test: Successful

Ice Type: Refrozen

Test temperature: -5° C

Horizontal Force:  $96 \pm 36$  lbs

Vertical Force:  $174 \pm 44$  lbs

## DF-25

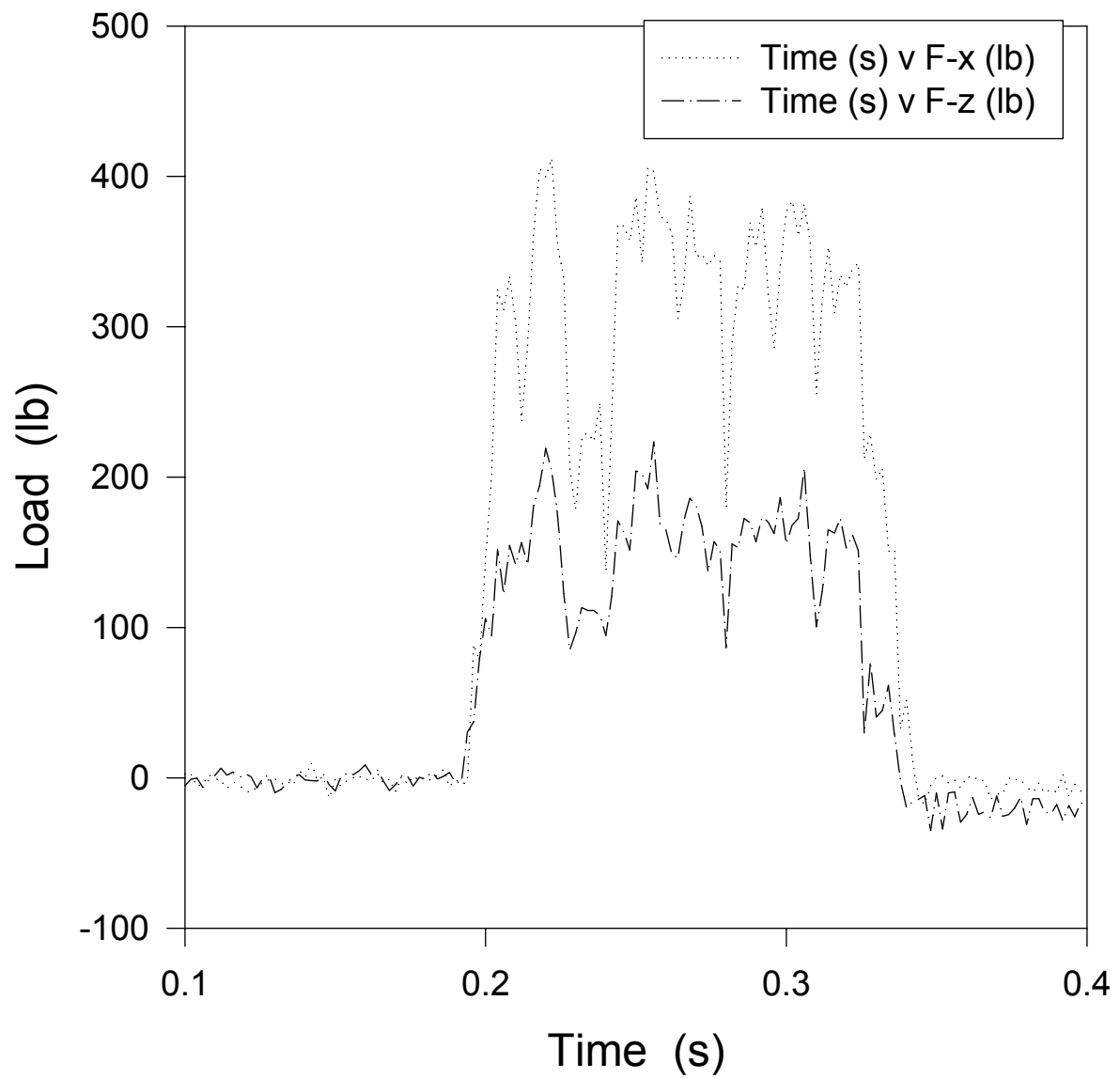


Figure A16: Sample DF-25 Load Trace

Test: Successful

Ice Type: Refrozen

Test temperature: -20° C

Horizontal Force:  $141 \pm 47$  lbs

Vertical Force:  $299 \pm 89$  lbs

## DF-26

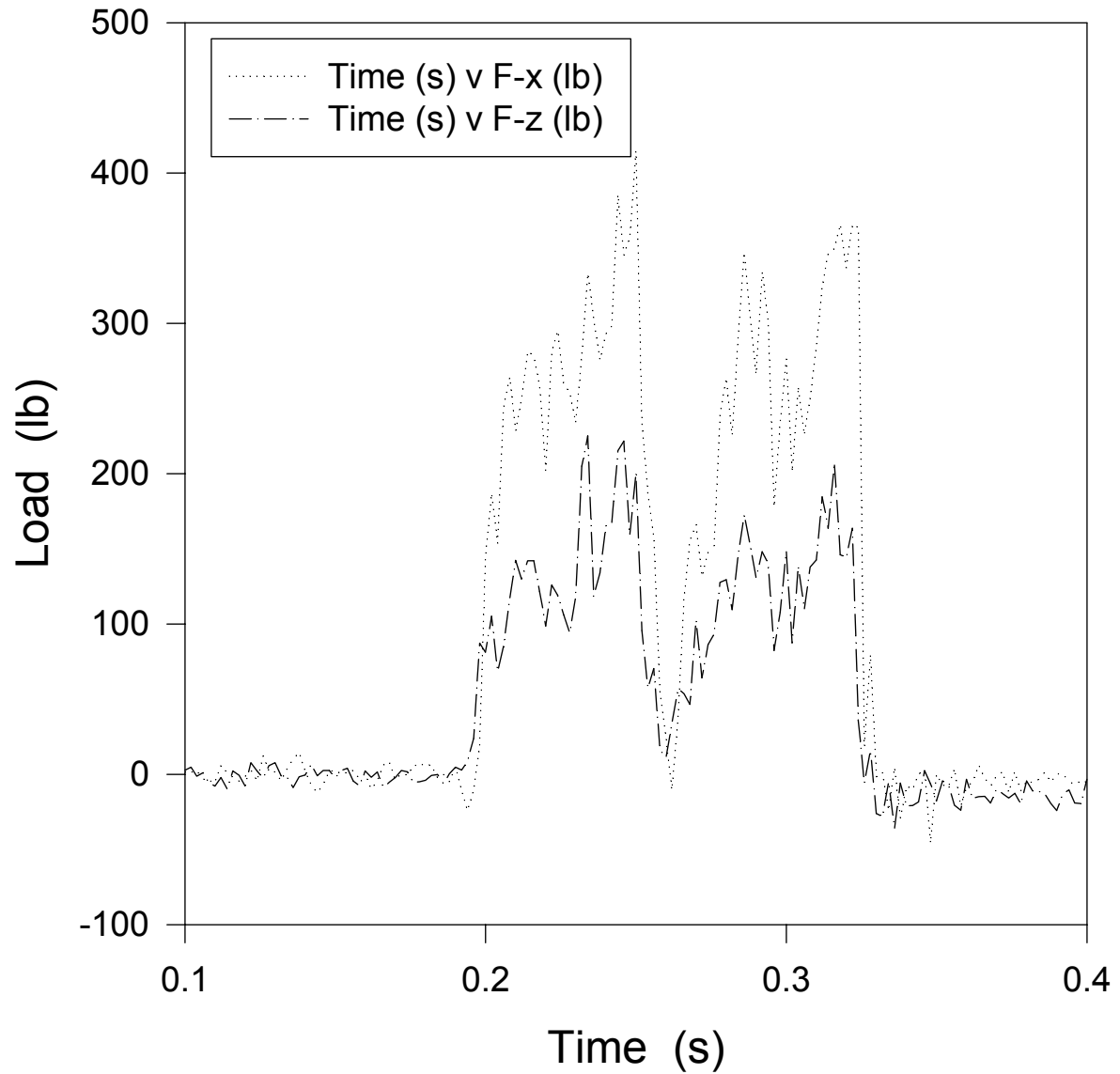


Figure A17: Sample DF-26 Load Trace

Test: Successful

Ice Type: Refrozen

Test temperature: -20° C

Horizontal Force:  $114 \pm 54$  lbs

Vertical Force:  $231 \pm 106$  lbs

## DF-27

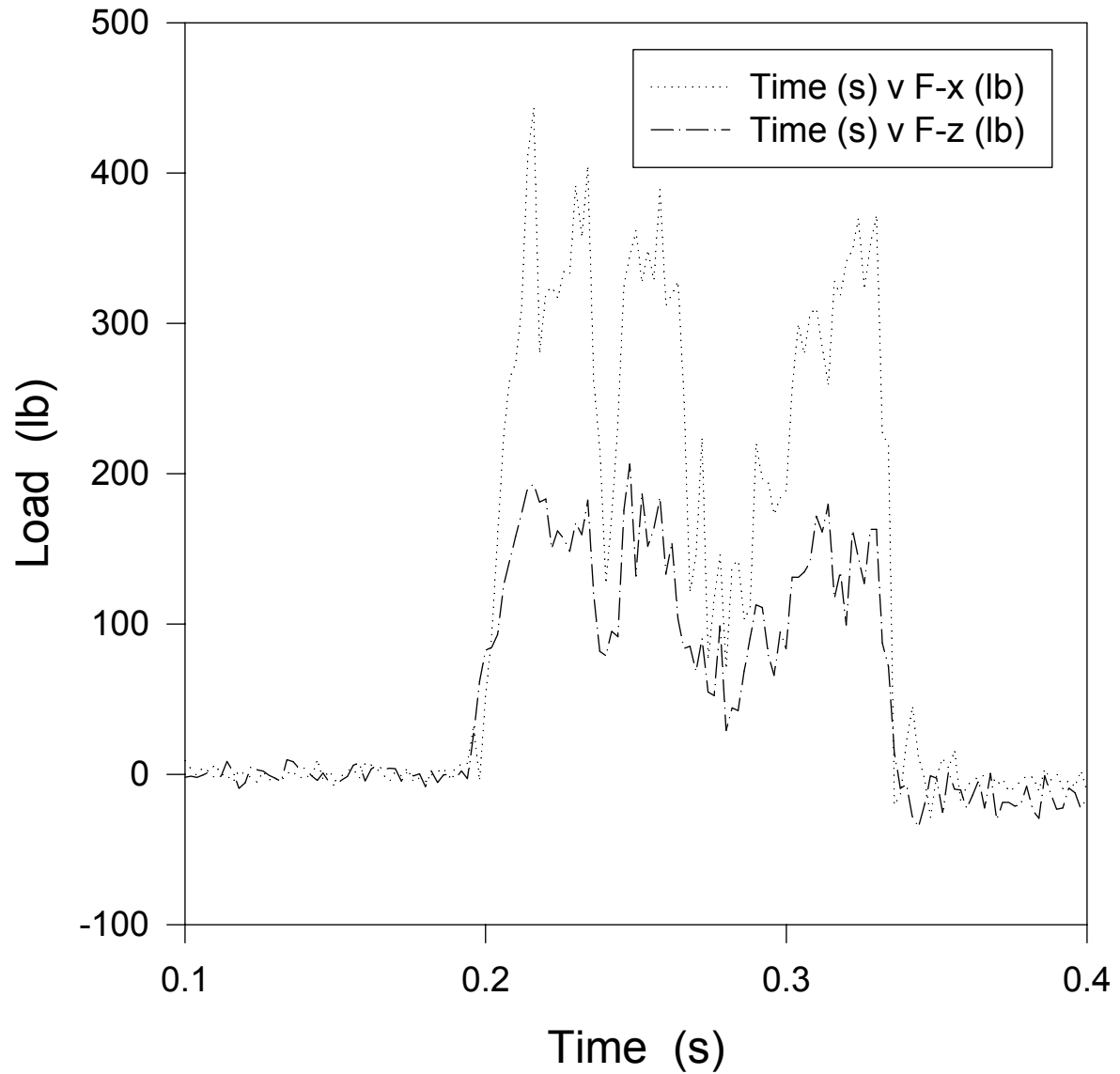


Figure A18: Sample DF-27 Load Trace

Test: Successful

Ice Type: Refrozen

Test temperature: -20° C

Horizontal Force:  $121 \pm 47$  lbs

Vertical Force:  $249 \pm 108$  lbs



## DF-28

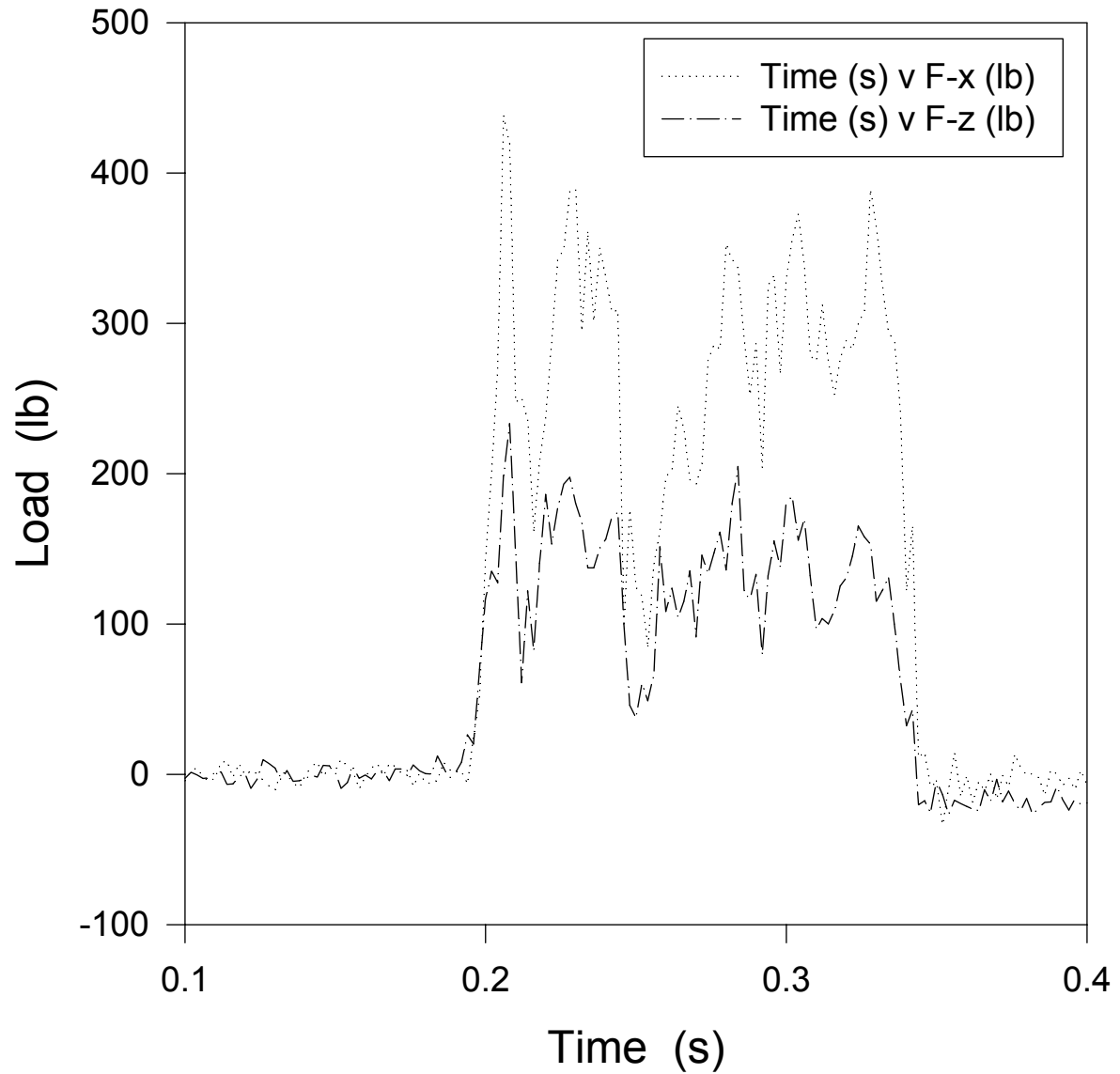


Figure A19: Sample DF-28 Load Trace

Test: Successful

Ice Type: Refrozen

Test temperature: -20° C

Horizontal Force:  $126 \pm 48$  lbs

Vertical Force:  $257 \pm 96$  lbs

## DF-30

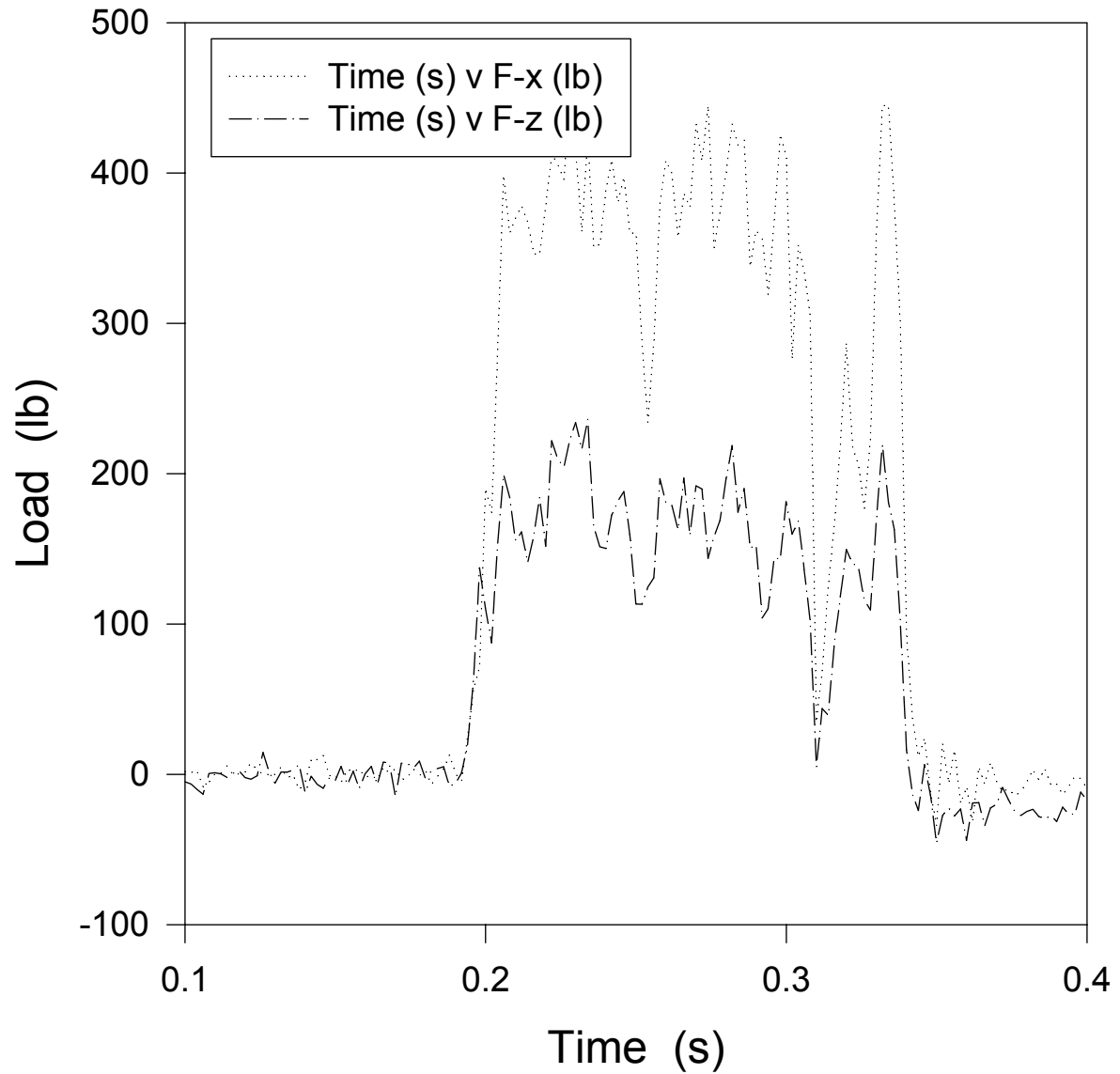


Figure A20: Sample DF-30 Load Trace  
Test: Successful  
Ice Type: Refrozen  
Test temperature:  $-20^{\circ}\text{C}$   
Horizontal Force:  $151 \pm 50$  lbs  
Vertical Force:  $324 \pm 109$  lbs

## DC-01

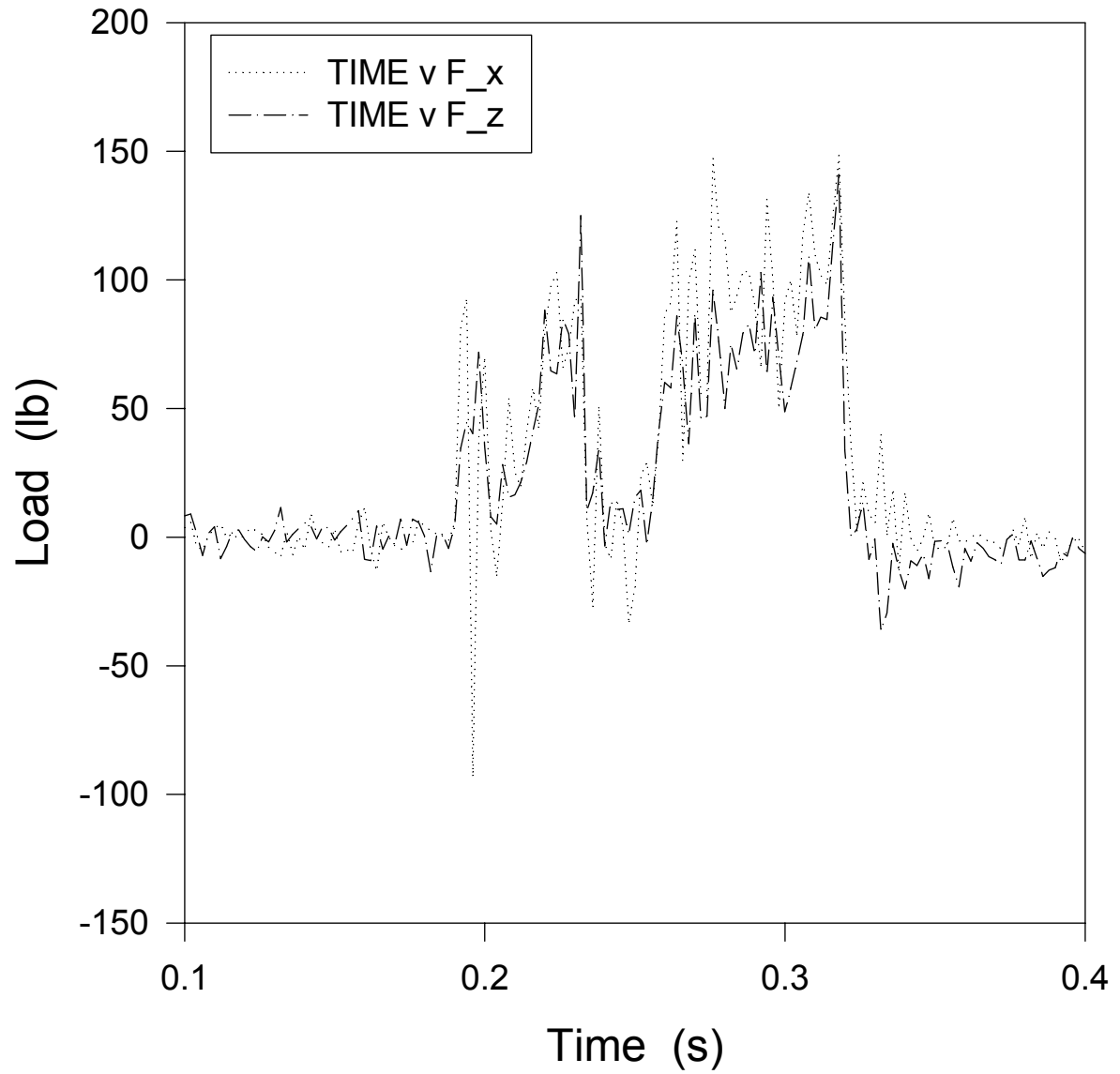


Figure A21: Sample DC-01 Load Trace  
Test: Successful  
Ice Type: Compacted Frozen Snow  
Test temperature:  $-1^{\circ}\text{C}$   
Horizontal Force:  $52 \pm 34$  lbs  
Vertical Force:  $62 \pm 50$  lbs

## DC-02

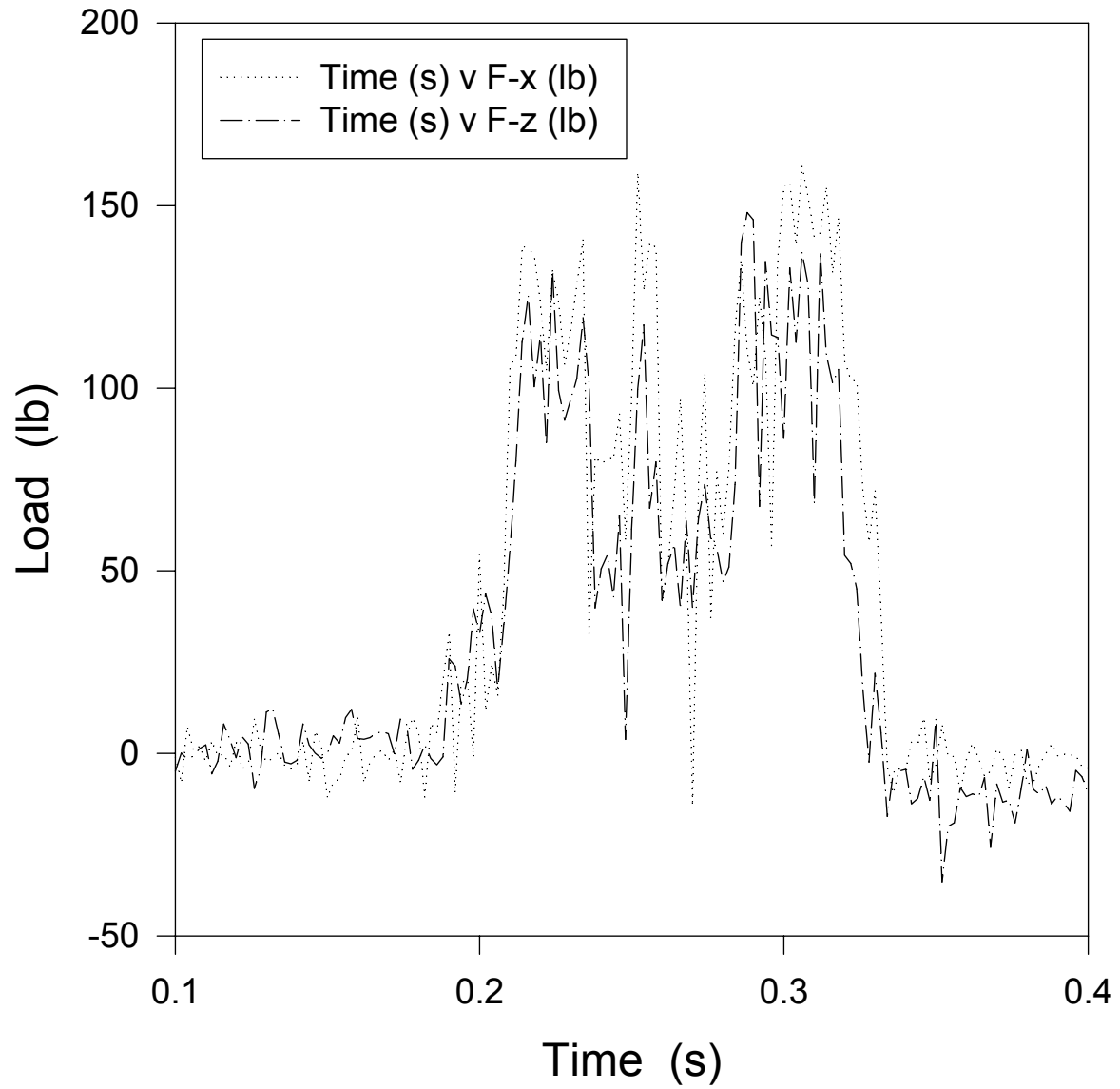


Figure A22: Sample DC-02 Load Trace  
Test: Successful  
Ice Type: Compacted Frozen Snow  
Test temperature:  $-1^{\circ}\text{C}$   
Horizontal Force:  $76 \pm 38$  lbs  
Vertical Force:  $94 \pm 46$  lbs

## DC-03

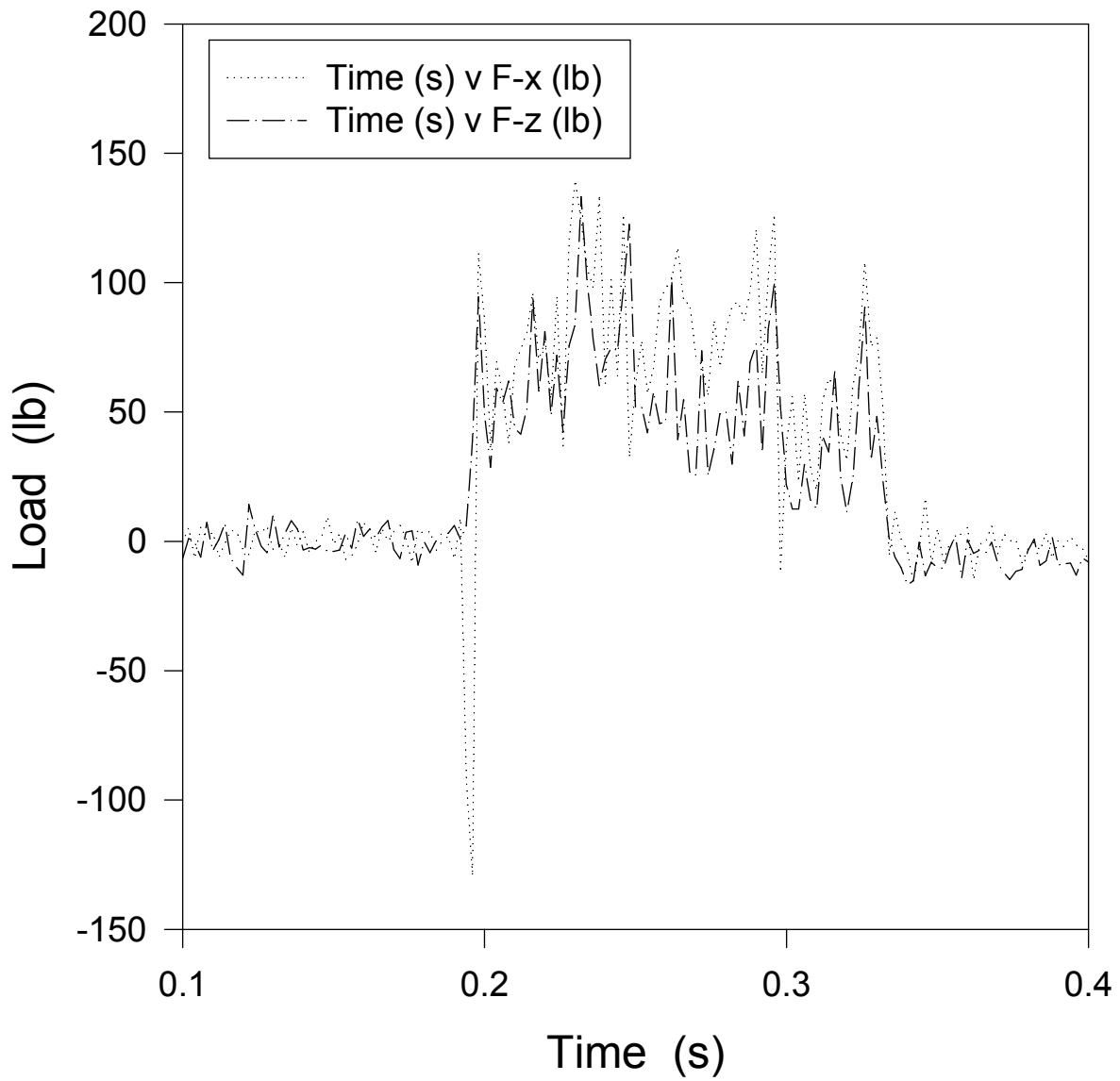


Figure A23: Sample DC-03 Load Trace  
Test: Successful  
Ice Type: Compacted Frozen Snow  
Test temperature:  $-1^{\circ}\text{C}$   
Horizontal Force:  $55 \pm 27$  lbs  
Vertical Force:  $75 \pm 30$  lbs

## DC-04

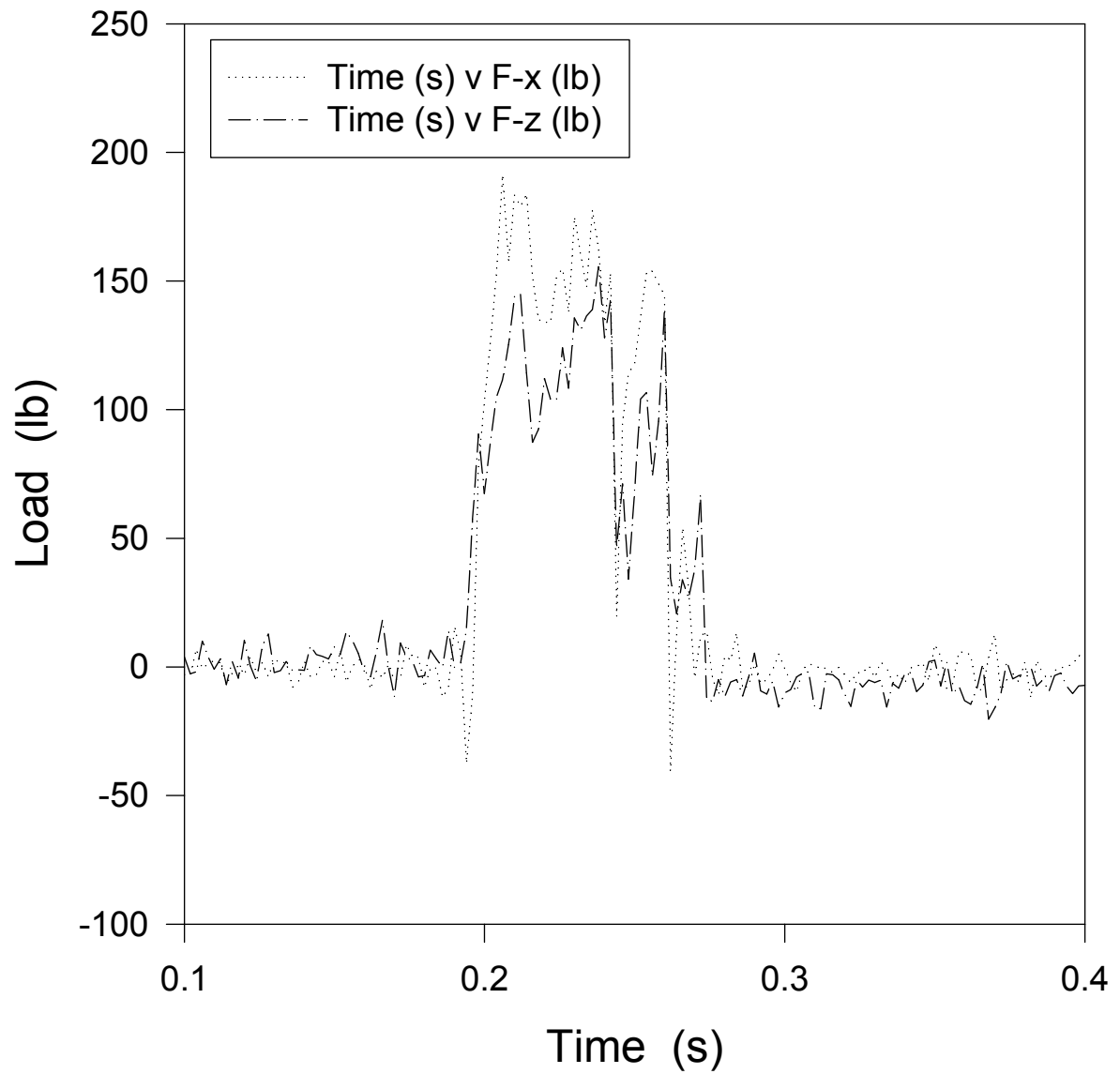


Figure A24: Sample DC-04 Load Trace  
Test: Successful  
Ice Type: Compacted Frozen Snow  
Test temperature:  $-1^{\circ}\text{C}$   
Horizontal Force:  $96 \pm 38$  lbs  
Vertical Force:  $121 \pm 59$  lbs

## DC-05

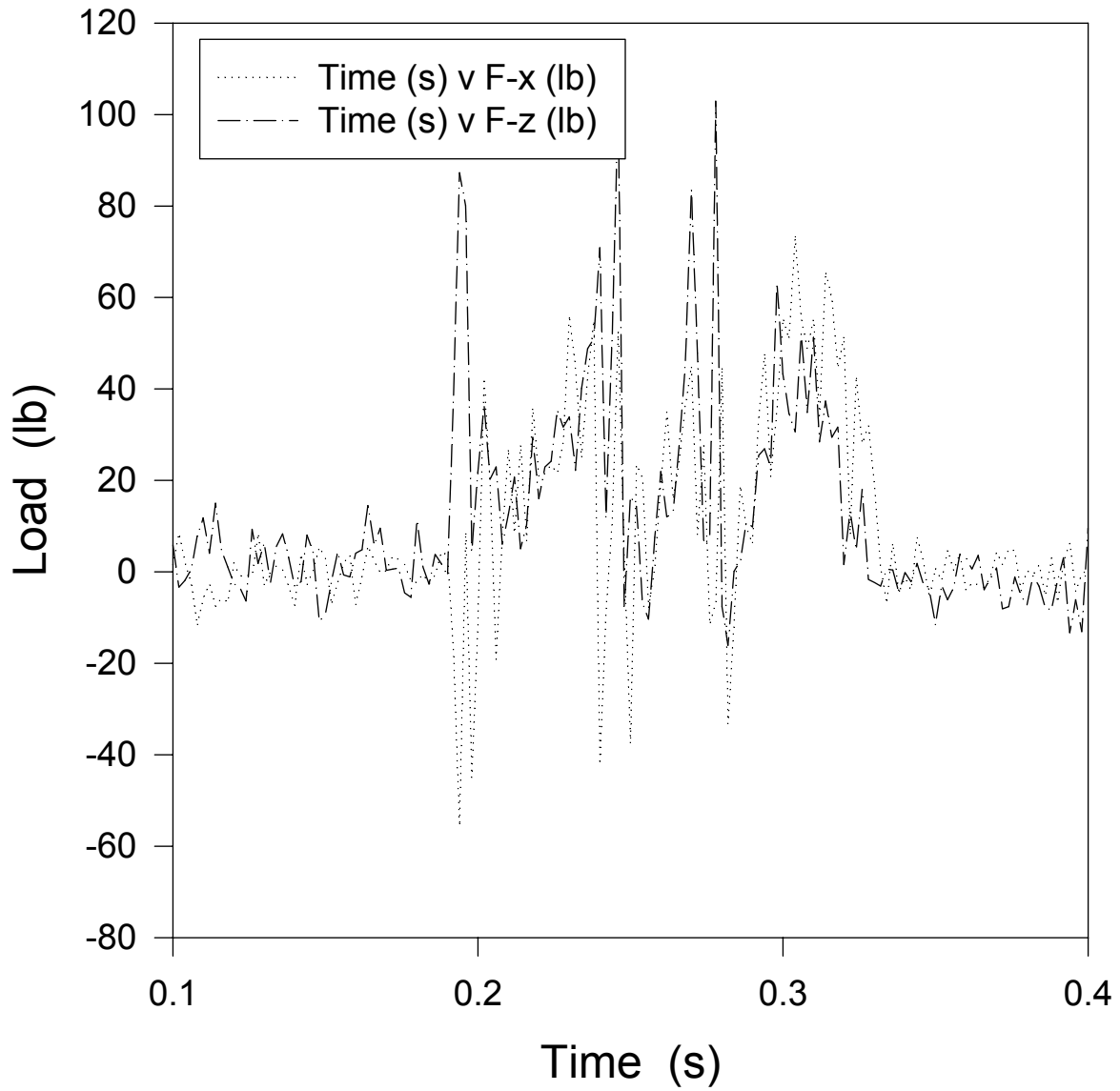


Figure A25: Sample DC-05 Load Trace  
Test: Unsuccessful  
Ice Type: Compacted Frozen Snow  
Test temperature:  $-1^{\circ}\text{C}$   
Horizontal Force:  $28 \pm 25$  lbs  
Vertical Force:  $21 \pm 28$  lbs

## DC-06

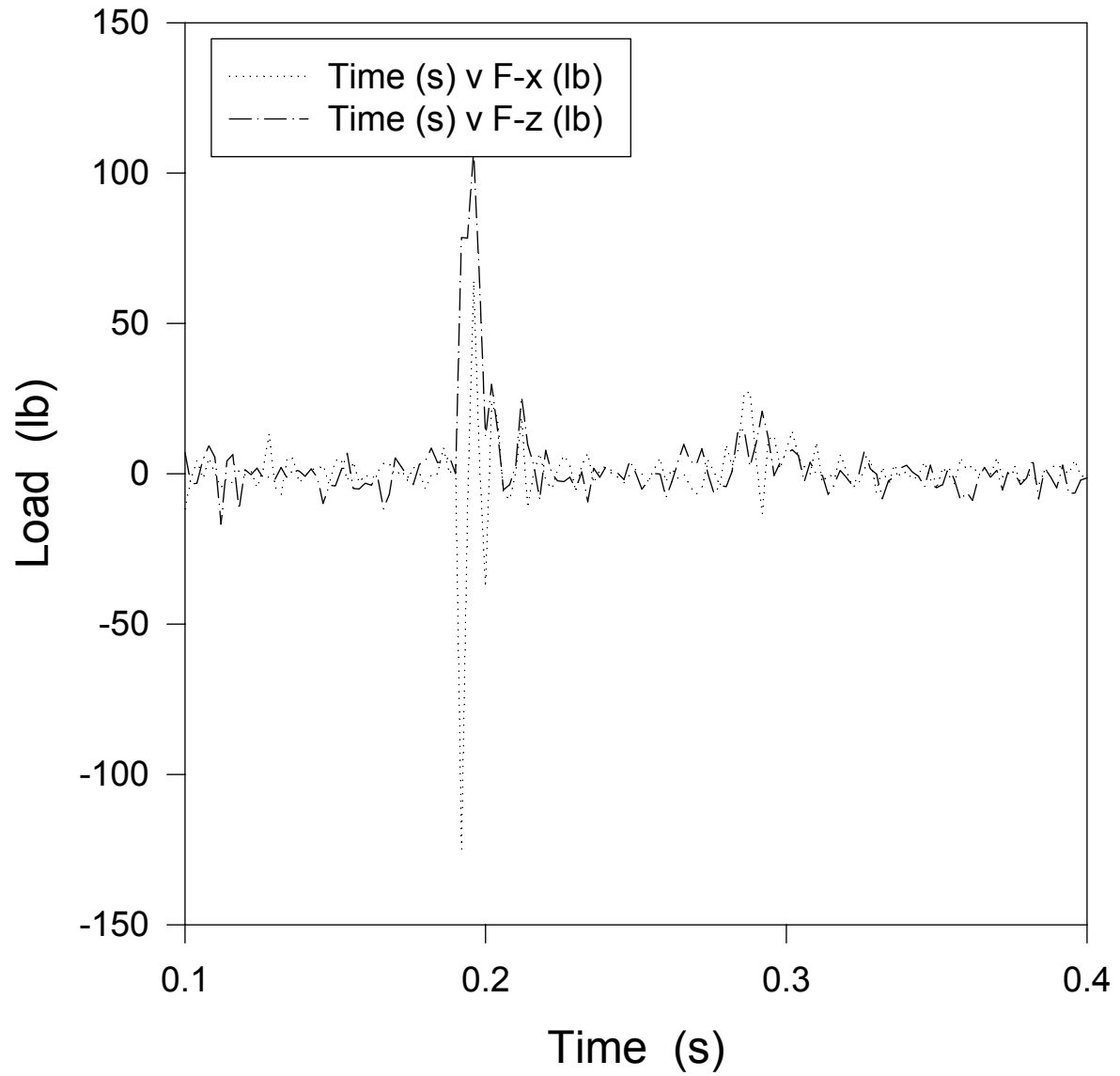


Figure A26: Sample DC-06 Load Trace  
Test: Unsuccessful  
Ice Type: Compacted Frozen Snow  
Test temperature:  $-1^{\circ}\text{C}$   
Horizontal Force:  $34 \pm 37$  lbs  
Vertical Force:  $-6 \pm 45$  lbs



## DC-13

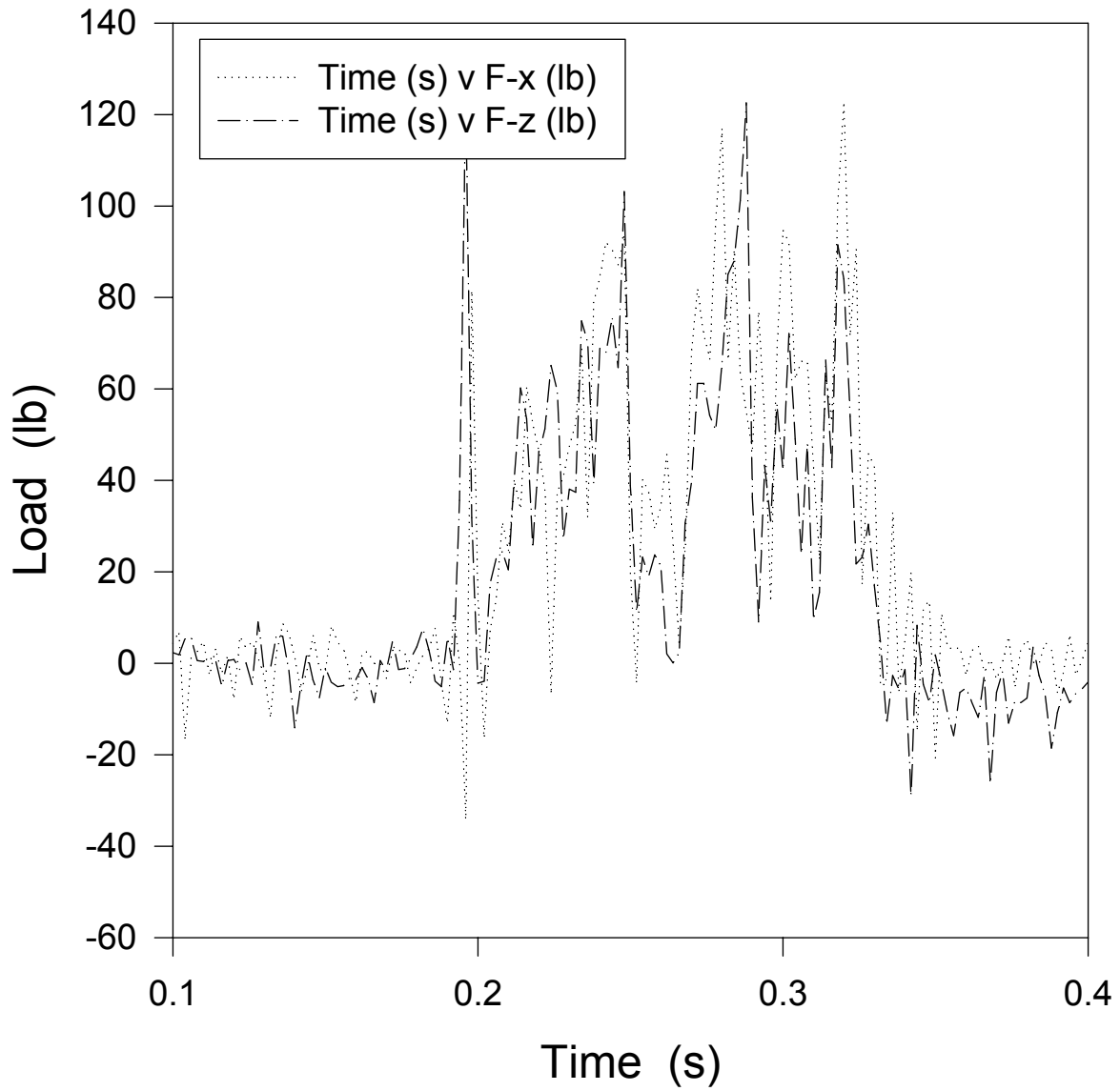


Figure A27: Sample DC-13 Load Trace  
Test: Successful  
Ice Type: Compacted Frozen Snow  
Test temperature: -5° C  
Horizontal Force:  $44 \pm 29$  lbs  
Vertical Force:  $50 \pm 33$  lbs

## DC-14

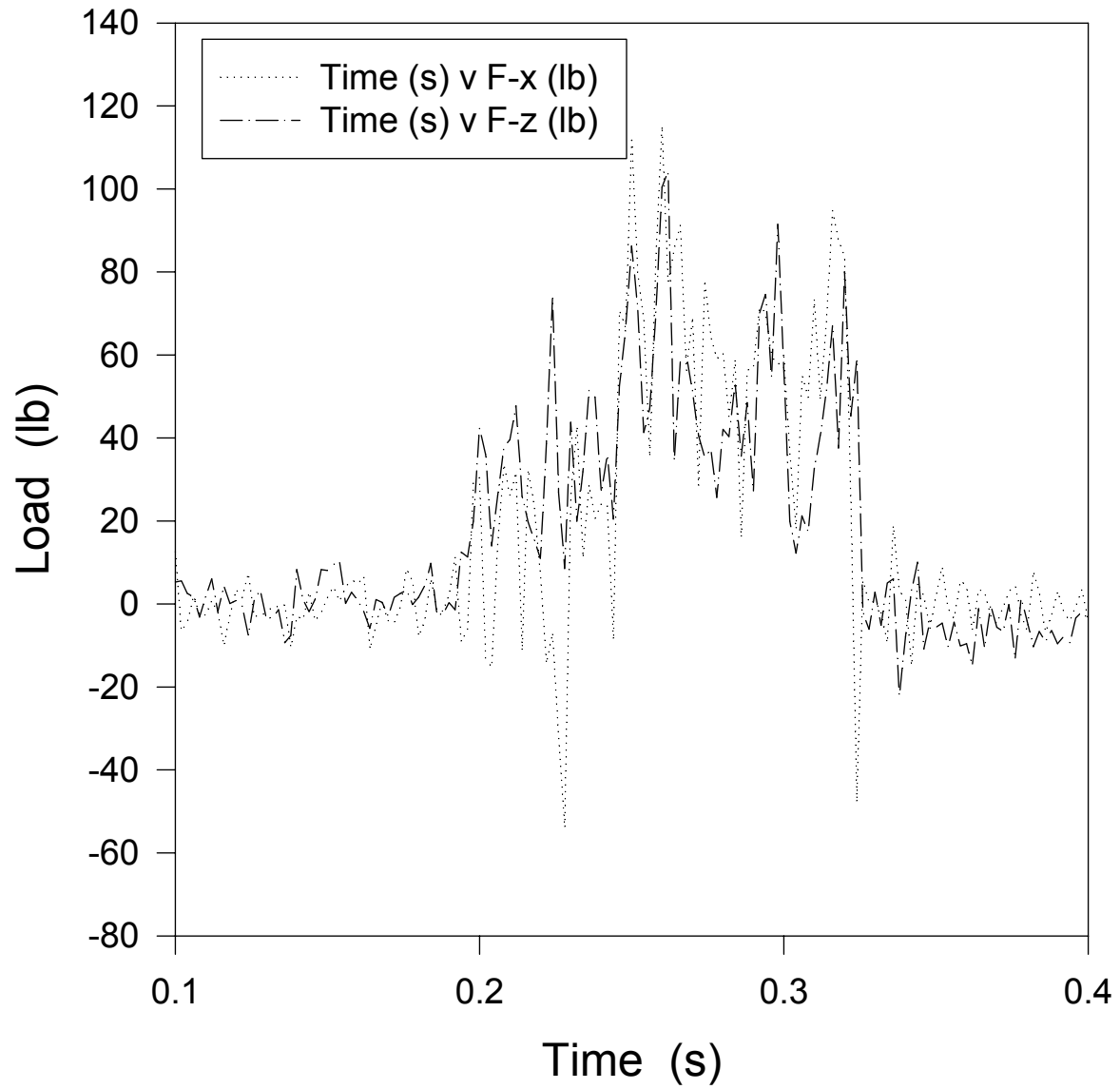


Figure A28: Sample DC-14 Load Trace  
Test: Successful  
Ice Type: Compacted Frozen Snow  
Test temperature:  $-5^{\circ}\text{C}$   
Horizontal Force:  $43 \pm 22$  lbs  
Vertical Force:  $41 \pm 37$  lbs

## DC-15

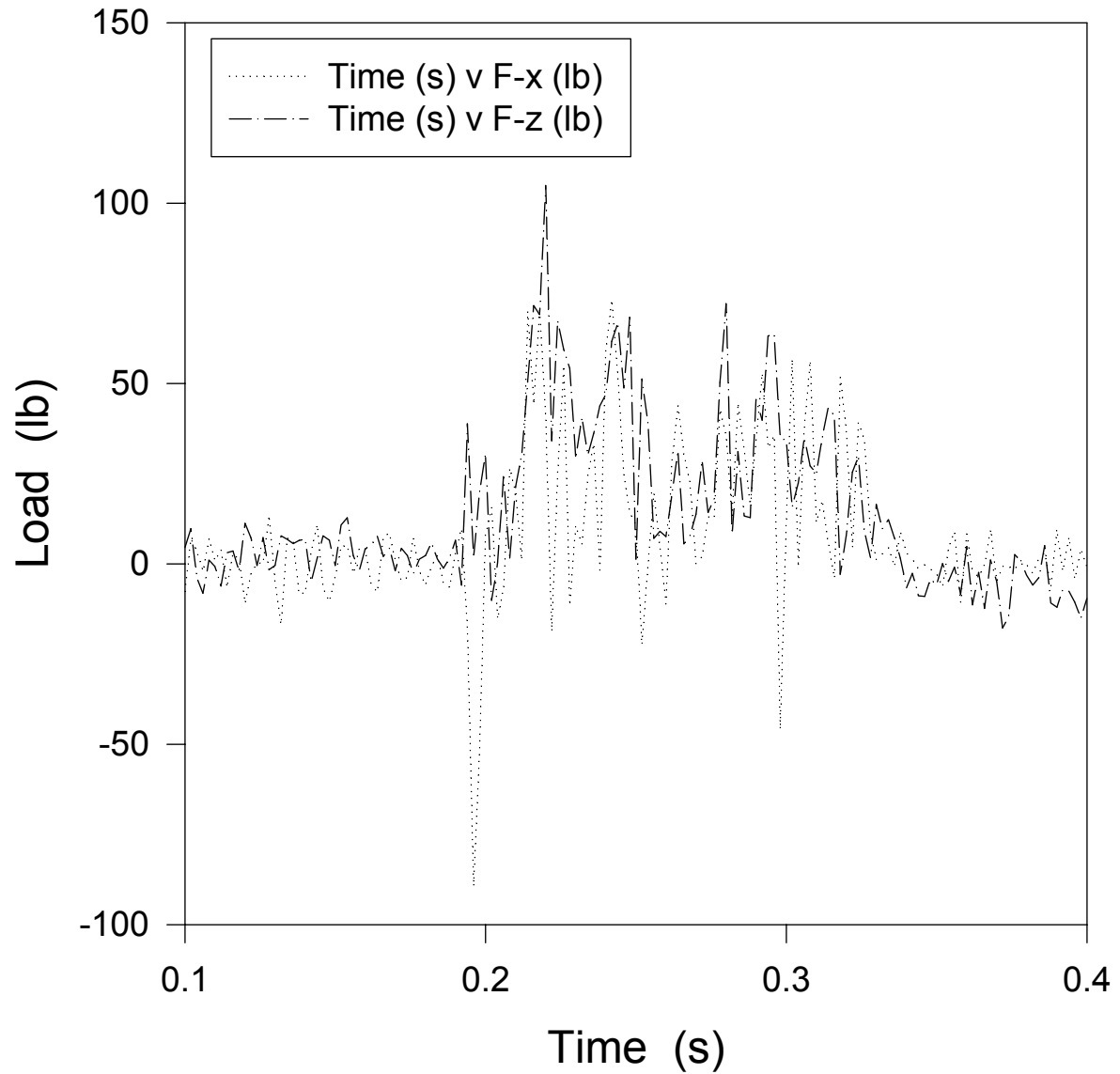


Figure A29: Sample DC-15 Load Trace  
Test: Unsuccessful  
Ice Type: Compacted Frozen Snow  
Test temperature:  $-5^{\circ}\text{C}$   
Horizontal Force:  $30 \pm 23$  lbs  
Vertical Force:  $18 \pm 28$  lbs

## DC-17

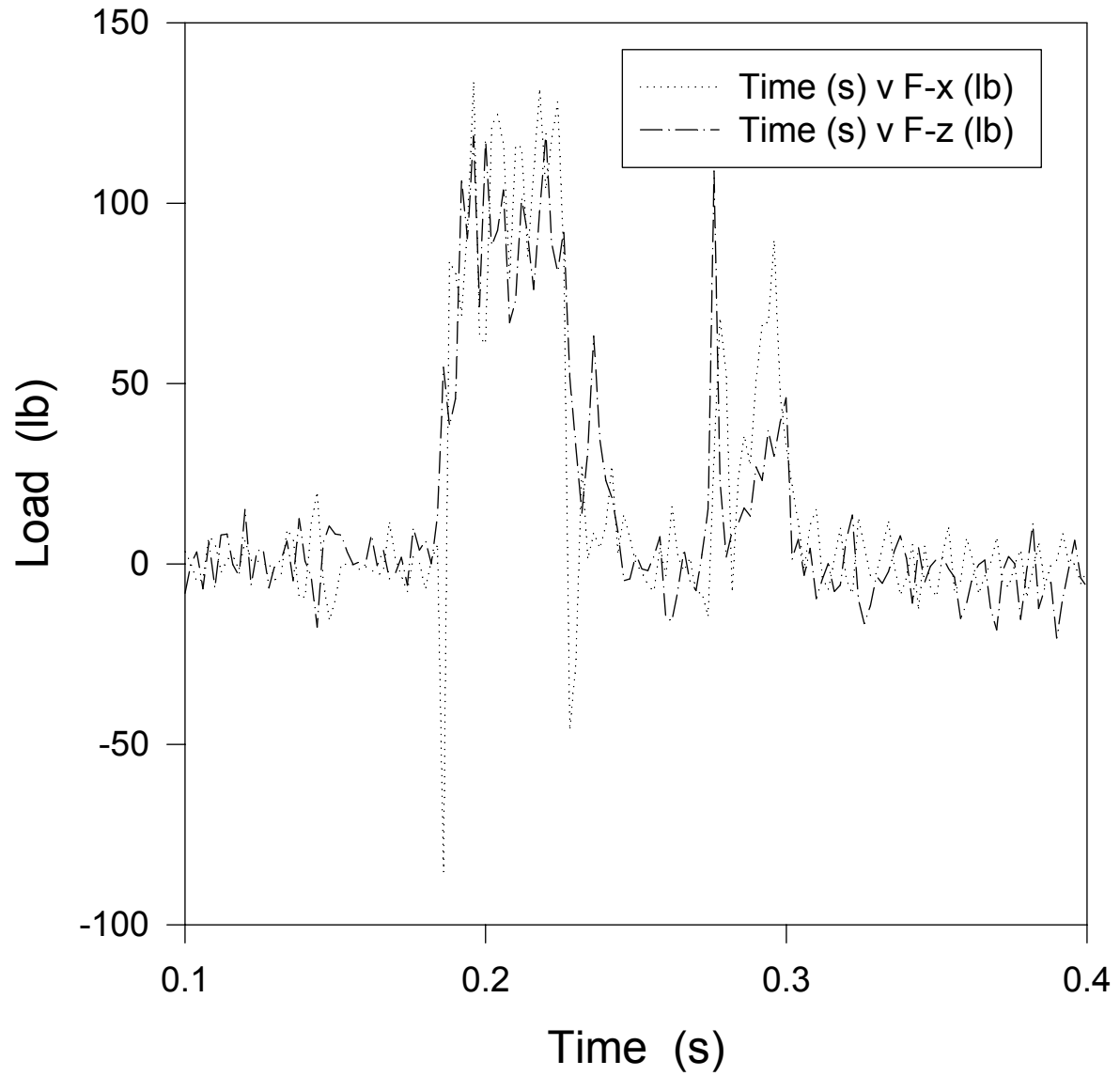


Figure A30: Sample DC-17 Load Trace  
Test: Unsuccessful  
Ice Type: Compacted Frozen Snow  
Test temperature:  $-5^{\circ}\text{C}$   
Horizontal Force:  $41 \pm 41$  lbs  
Vertical Force:  $42 \pm 50$  lbs

## DC-18

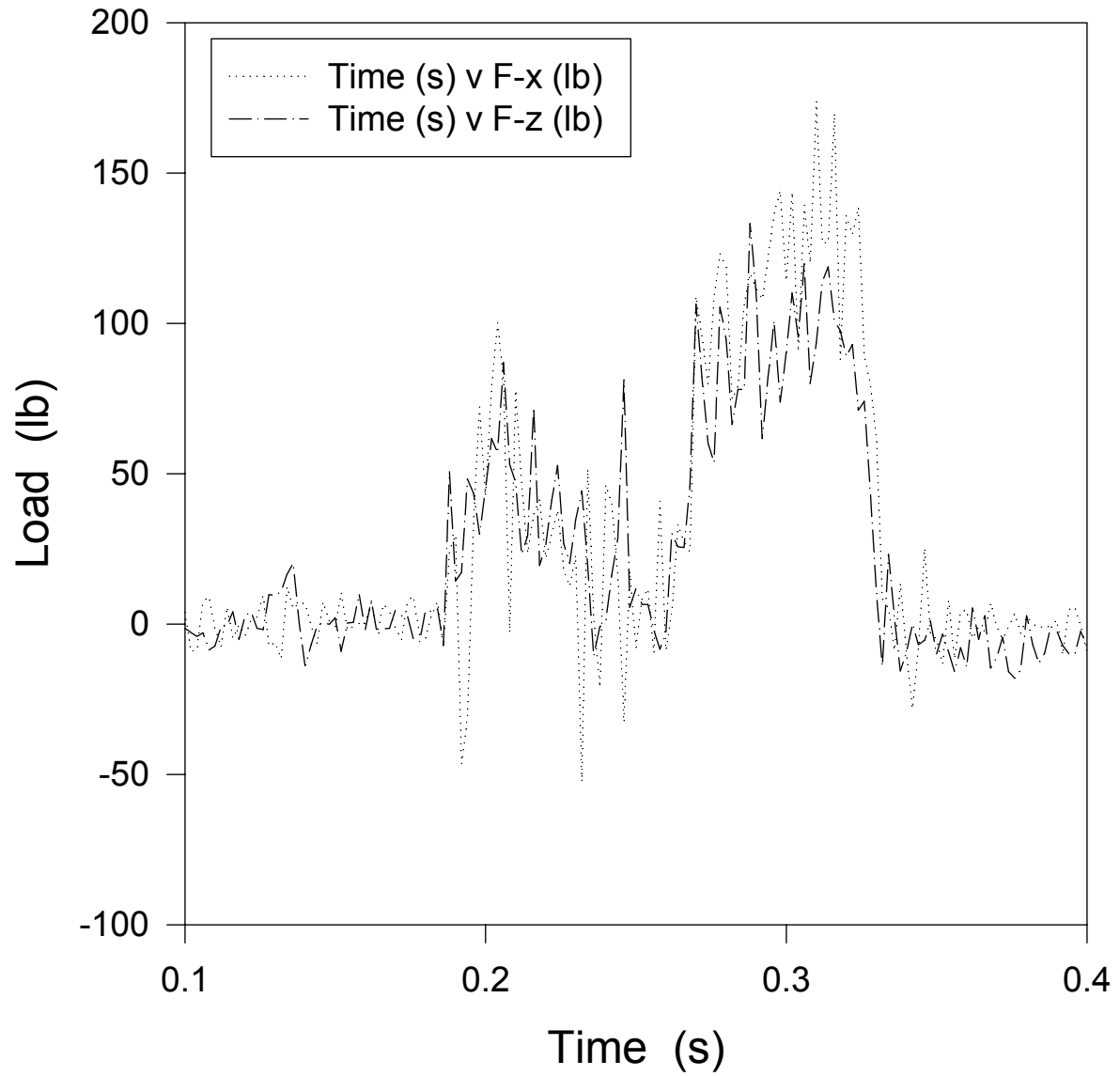


Figure A31: Sample DC-18 Load Trace  
Test: Successful  
Ice Type: Compacted Frozen Snow  
Test temperature: -5° C  
Horizontal Force:  $54 \pm 37$  lbs  
Vertical Force:  $63 \pm 55$  lbs

## DC-19

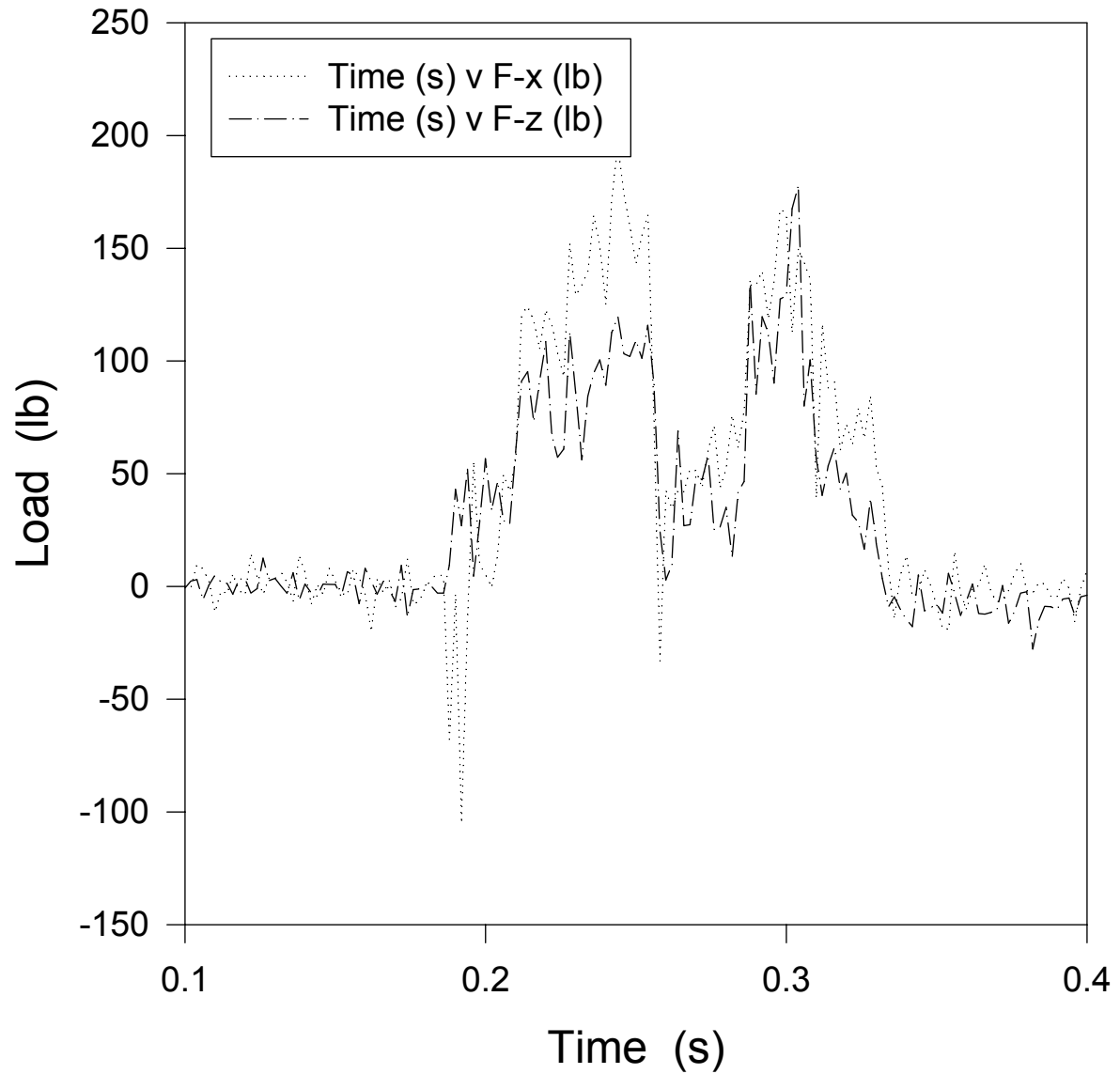


Figure A32: Sample DC-19 Load Trace  
Test: Successful  
Ice Type: Compacted Frozen Snow  
Test temperature:  $-5^{\circ}\text{C}$   
Horizontal Force:  $66 \pm 40$  lbs  
Vertical Force:  $86 \pm 60$  lbs

## DC-20

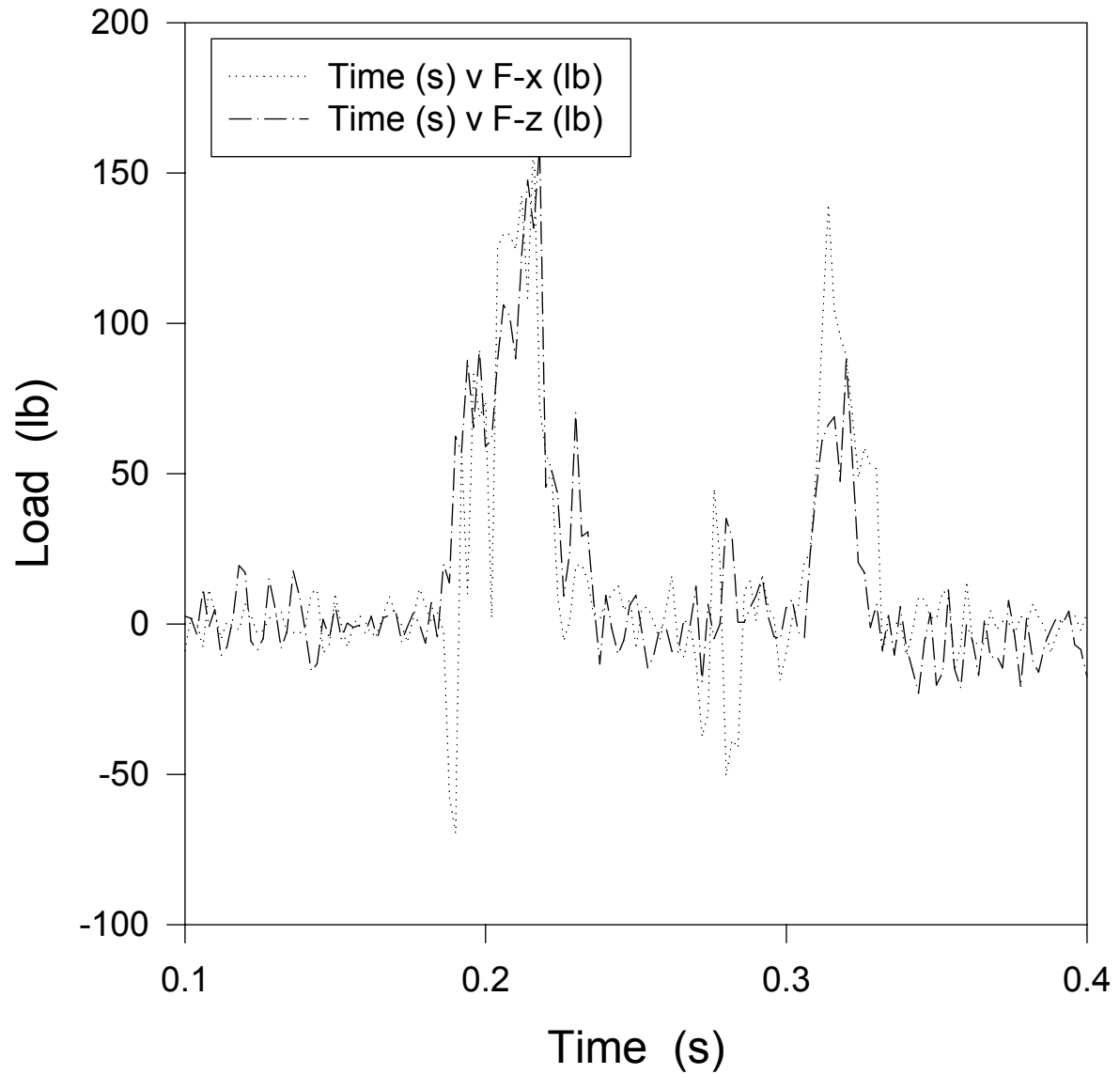


Figure A33: Sample DC-20 Load Trace  
Test: Unsuccessful  
Ice Type: Compacted Frozen Snow  
Test temperature:  $-5^{\circ}\text{C}$   
Horizontal Force:  $32 \pm 42$  lbs  
Vertical Force:  $29 \pm 52$  lbs

## DC-21

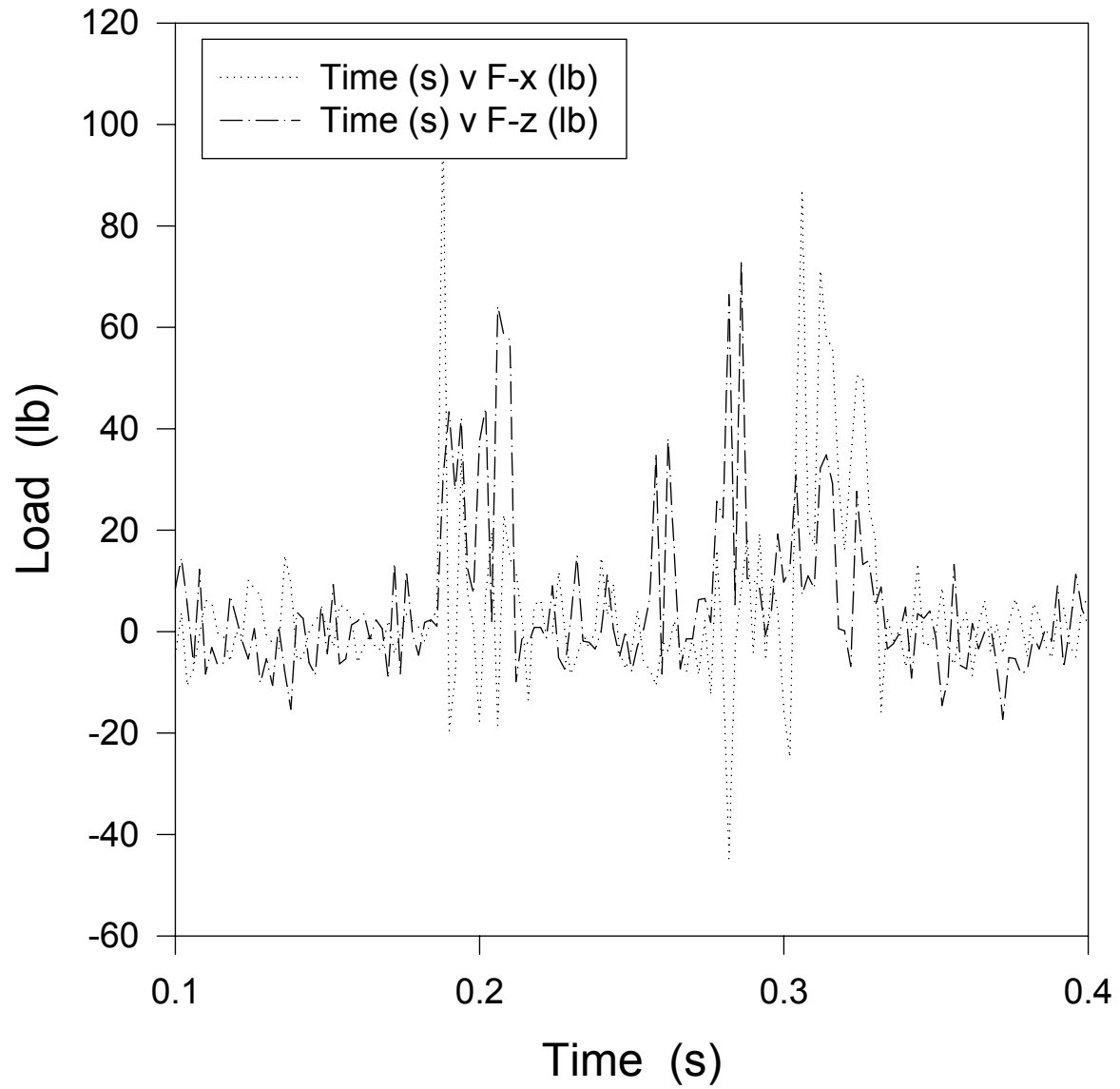


Figure A34: Sample DC-21 Load Trace  
Test: Unsuccessful  
Ice Type: Compacted Frozen Snow  
Test temperature: -5° C  
Horizontal Force:  $14 \pm 20$  lbs  
Vertical Force:  $9 \pm 25$  lbs



## DC-22

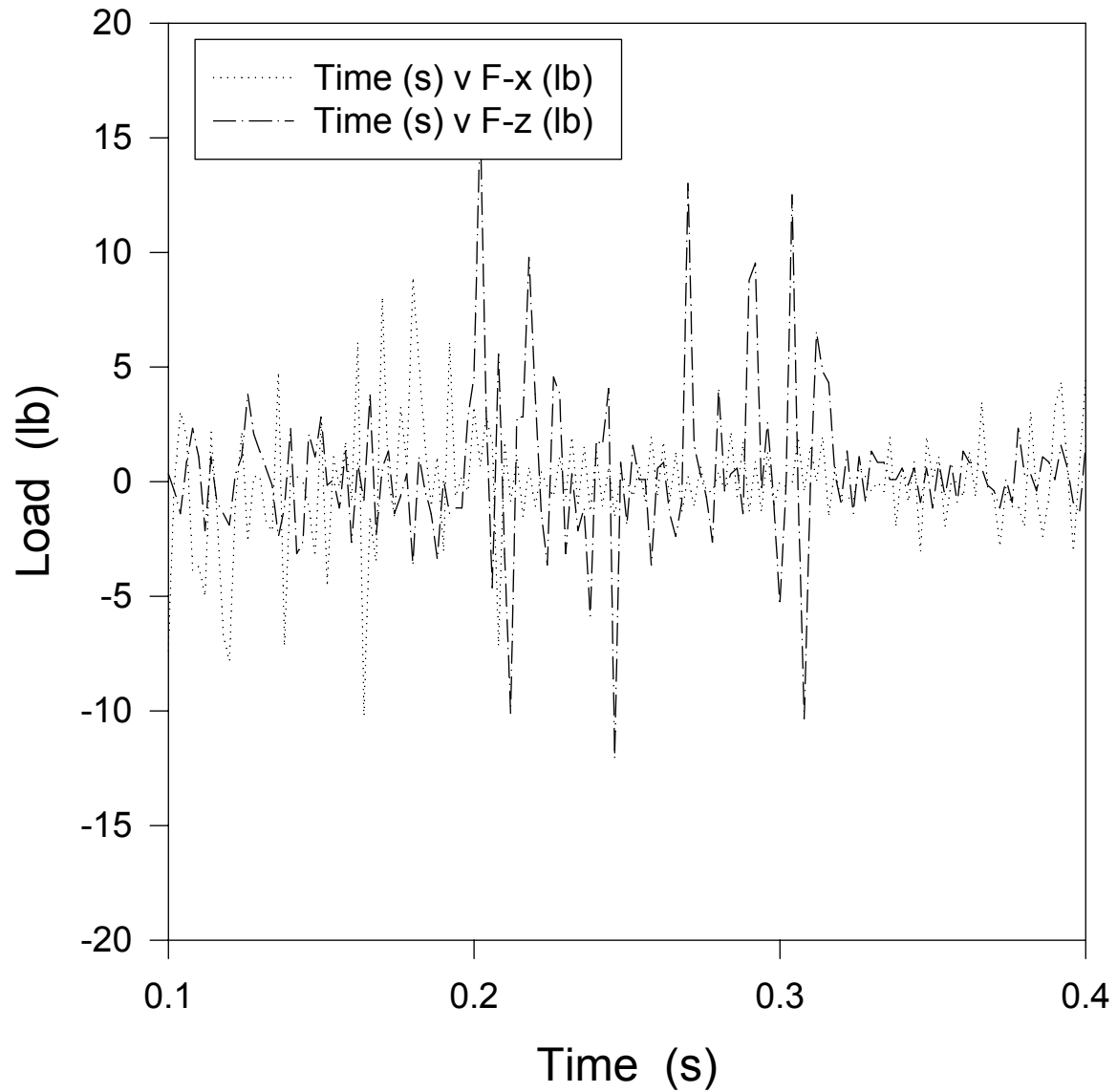


Figure A35: Sample DC-22 Load Trace  
Test: Unsuccessful  
Ice Type: Compacted Frozen Snow  
Test temperature: -5° C  
Horizontal Force:  $1 \pm 4$  lbs  
Vertical Force:  $0 \pm 2$  lbs

## DC-23

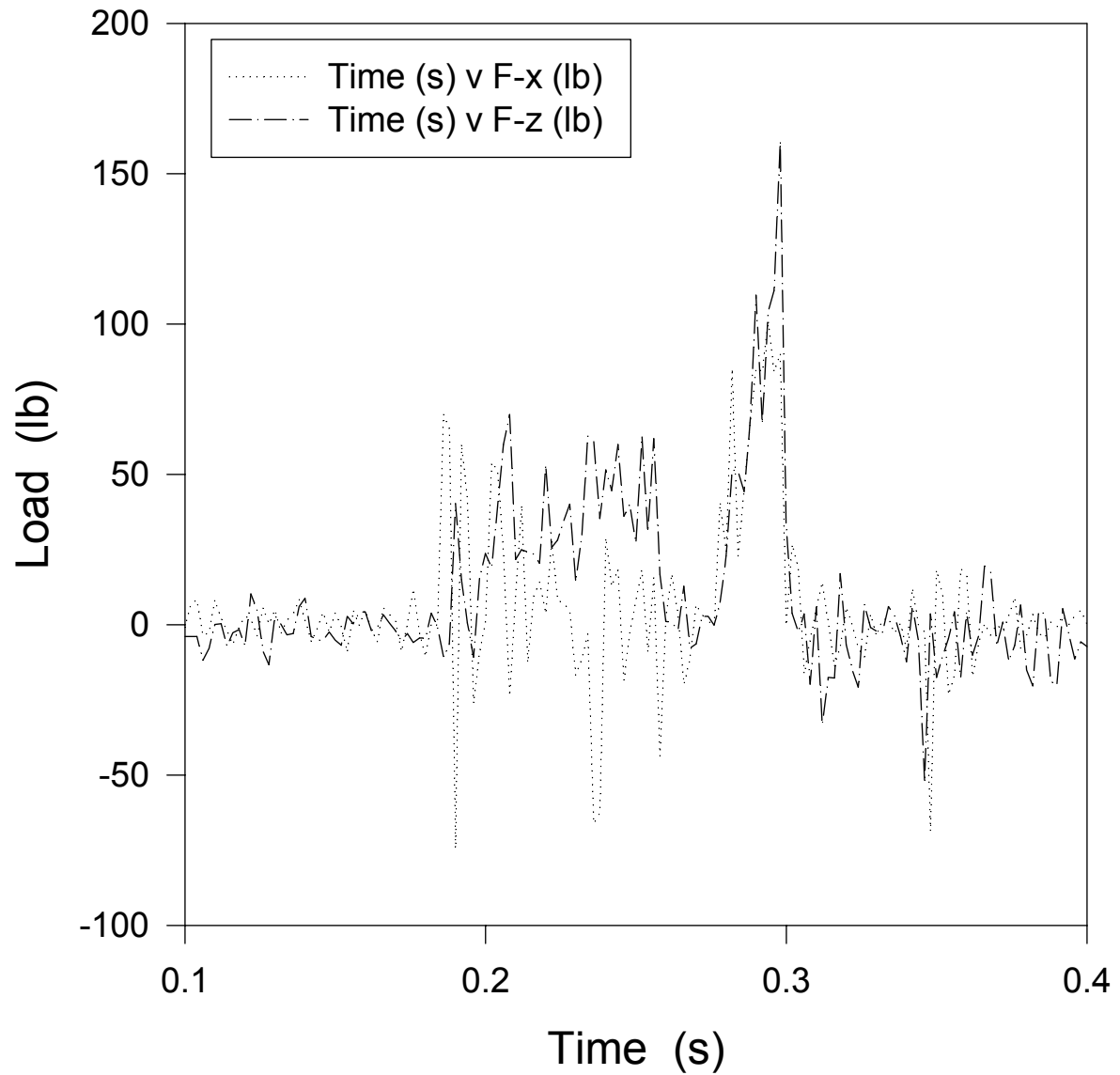


Figure A36: Sample DC-23 Load Trace  
Test: Unsuccessful  
Ice Type: Compacted Frozen Snow  
Test temperature:  $-5^{\circ}\text{C}$   
Horizontal Force:  $36 \pm 33$  lbs  
Vertical Force:  $15 \pm 38$  lbs

## DC-24

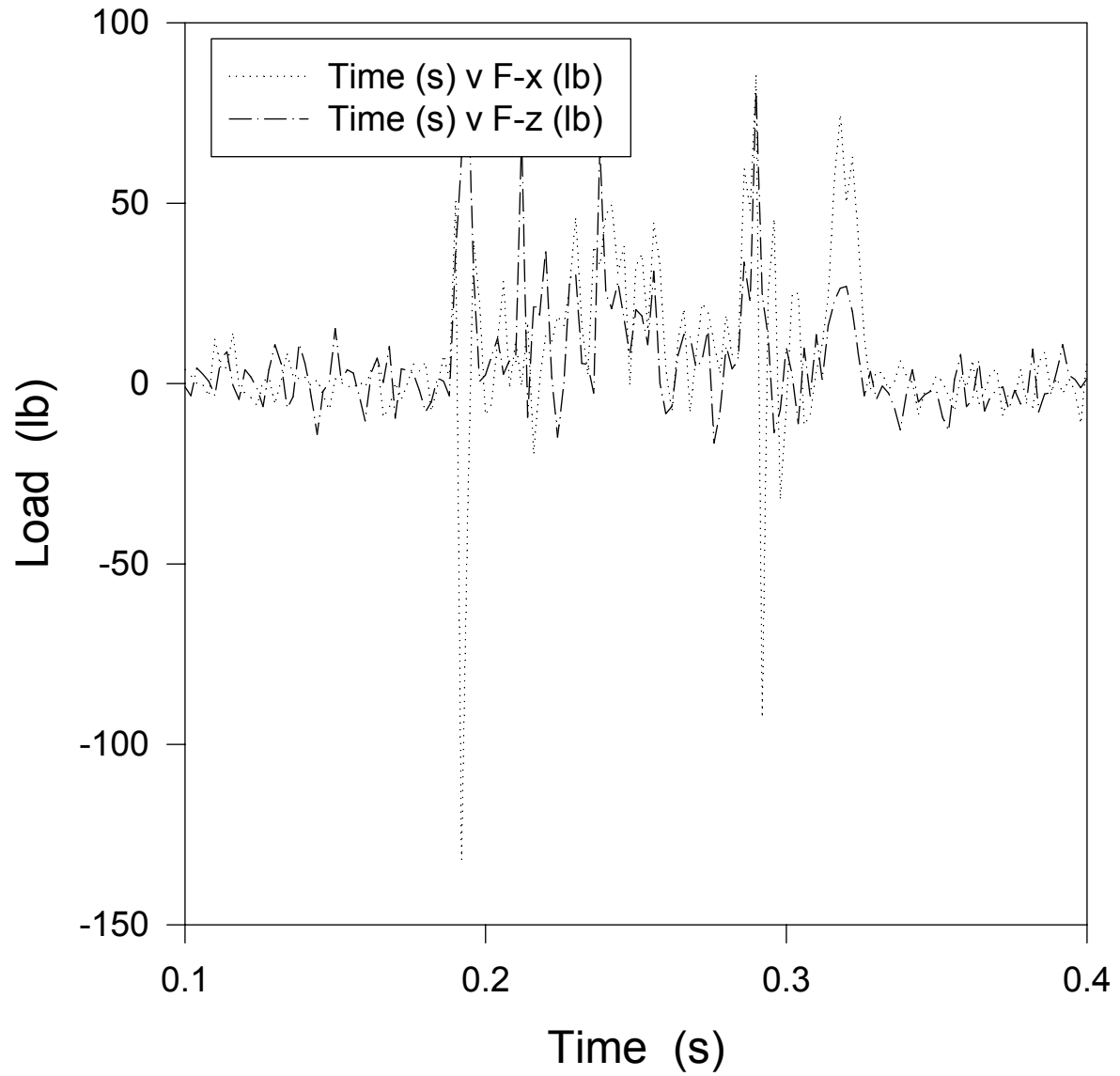


Figure A37: Sample DC-24 Load Trace  
Test: Unsuccessful  
Ice Type: Compacted Frozen Snow  
Test temperature:  $-5^{\circ}\text{C}$   
Horizontal Force:  $11 \pm 20$  lbs  
Vertical Force:  $13 \pm 30$  lbs

## DC-25

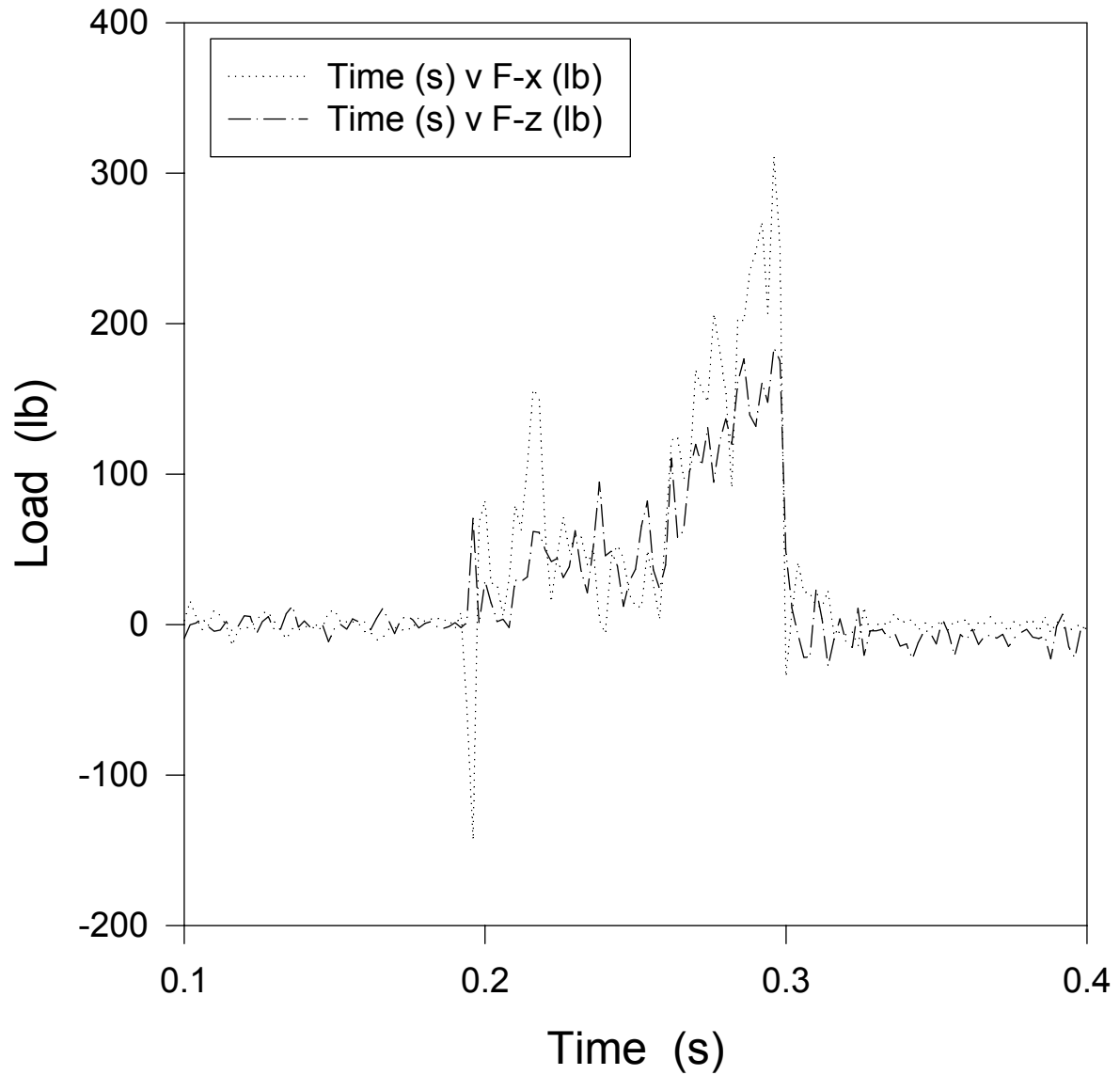


Figure A38: Sample DC-25 Load Trace  
Test: Successful  
Ice Type: Compacted Frozen Snow  
Test temperature: -20° C  
Horizontal Force: 70 ± 52 lbs  
Vertical Force: 90 ± 88 lbs

## DC-26

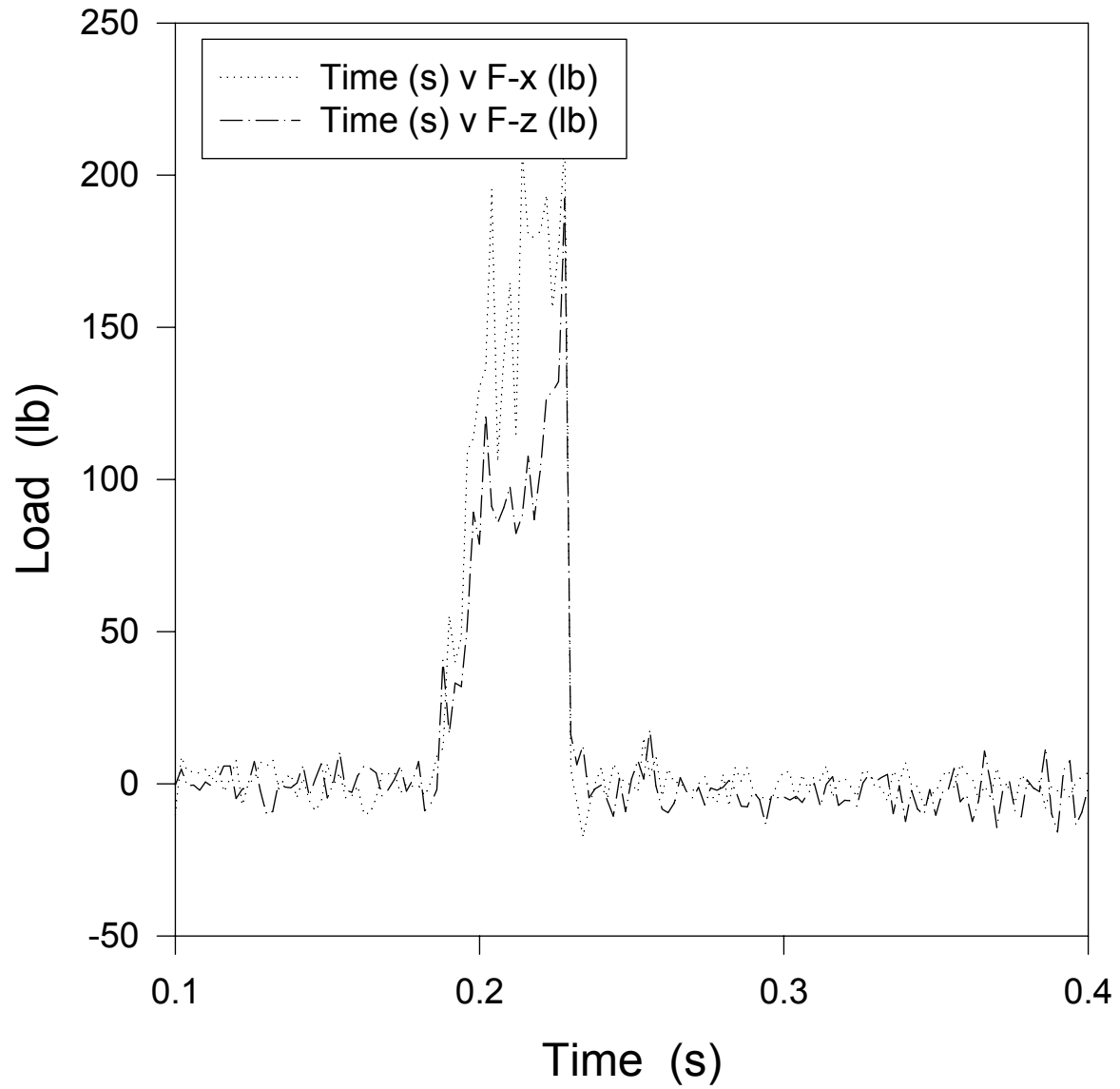


Figure A39: Sample DC-26 Load Trace  
Test: Successful  
Ice Type: Compacted Frozen Snow  
Test temperature: -20° C  
Horizontal Force:  $80 \pm 46$  lbs  
Vertical Force:  $118 \pm 73$  lbs

## DC-27

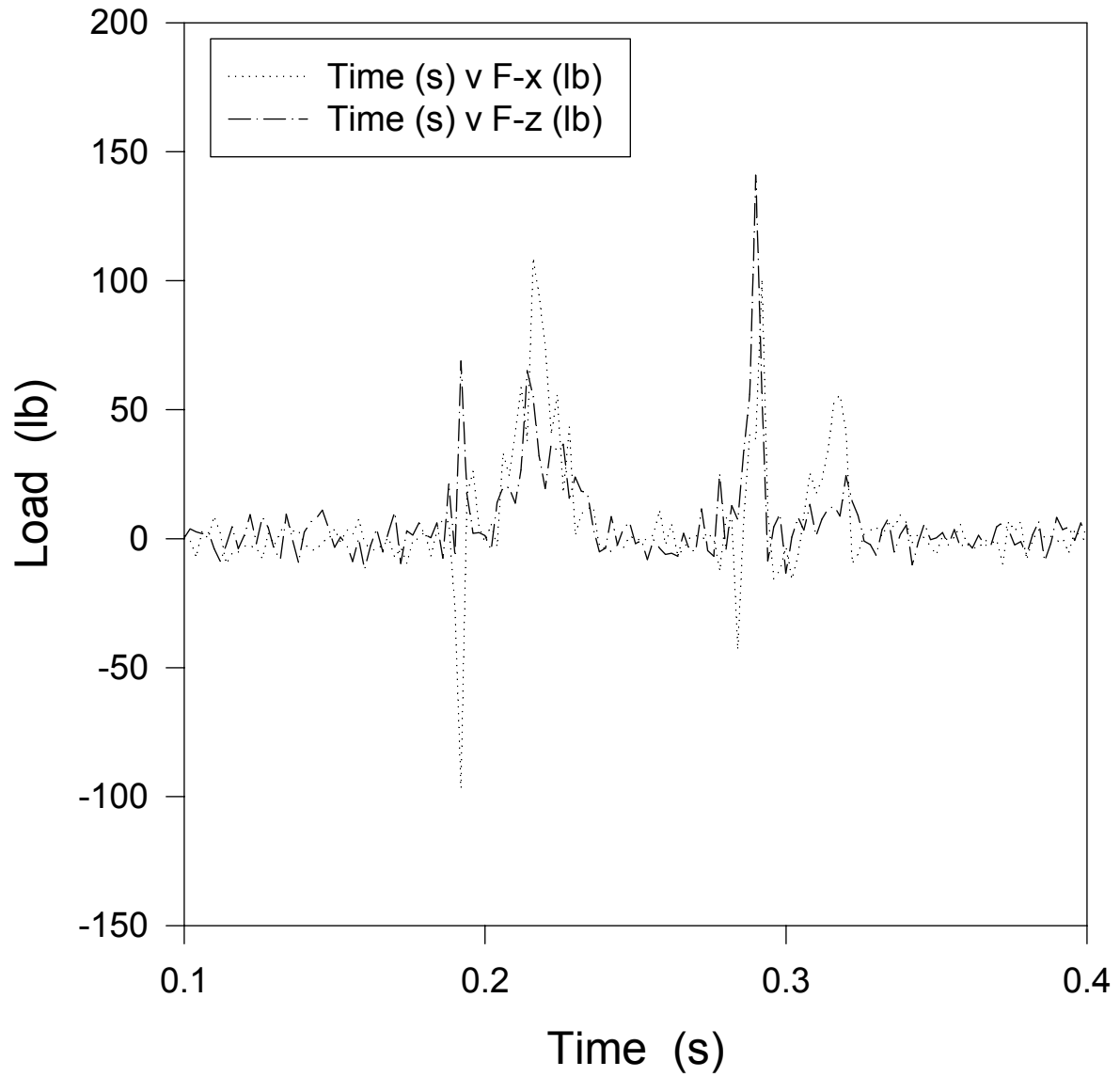


Figure A40: Sample DC-27 Load Trace  
Test: Unsuccessful  
Ice Type: Compacted Frozen Snow  
Test temperature: -20° C  
Horizontal Force:  $14 \pm 24$  lbs  
Vertical Force:  $14 \pm 32$  lbs

## DC-28

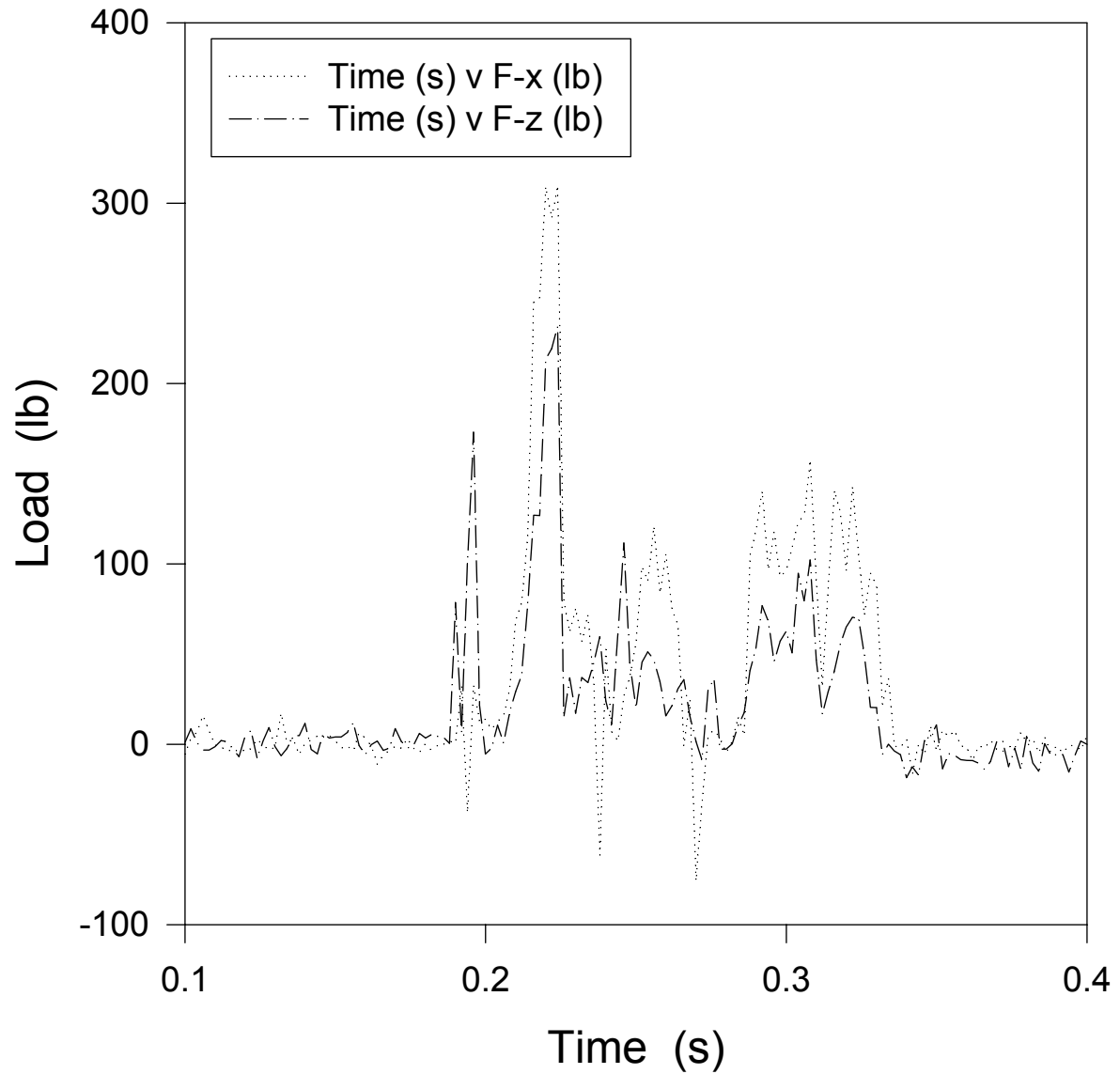


Figure A41: Sample DC-28 Load Trace  
Test: Unsuccessful  
Ice Type: Compacted Frozen Snow  
Test temperature: -20° C  
Horizontal Force: 50 ± 50 lbs  
Vertical Force: 74 ± 77 lbs

## DC-29

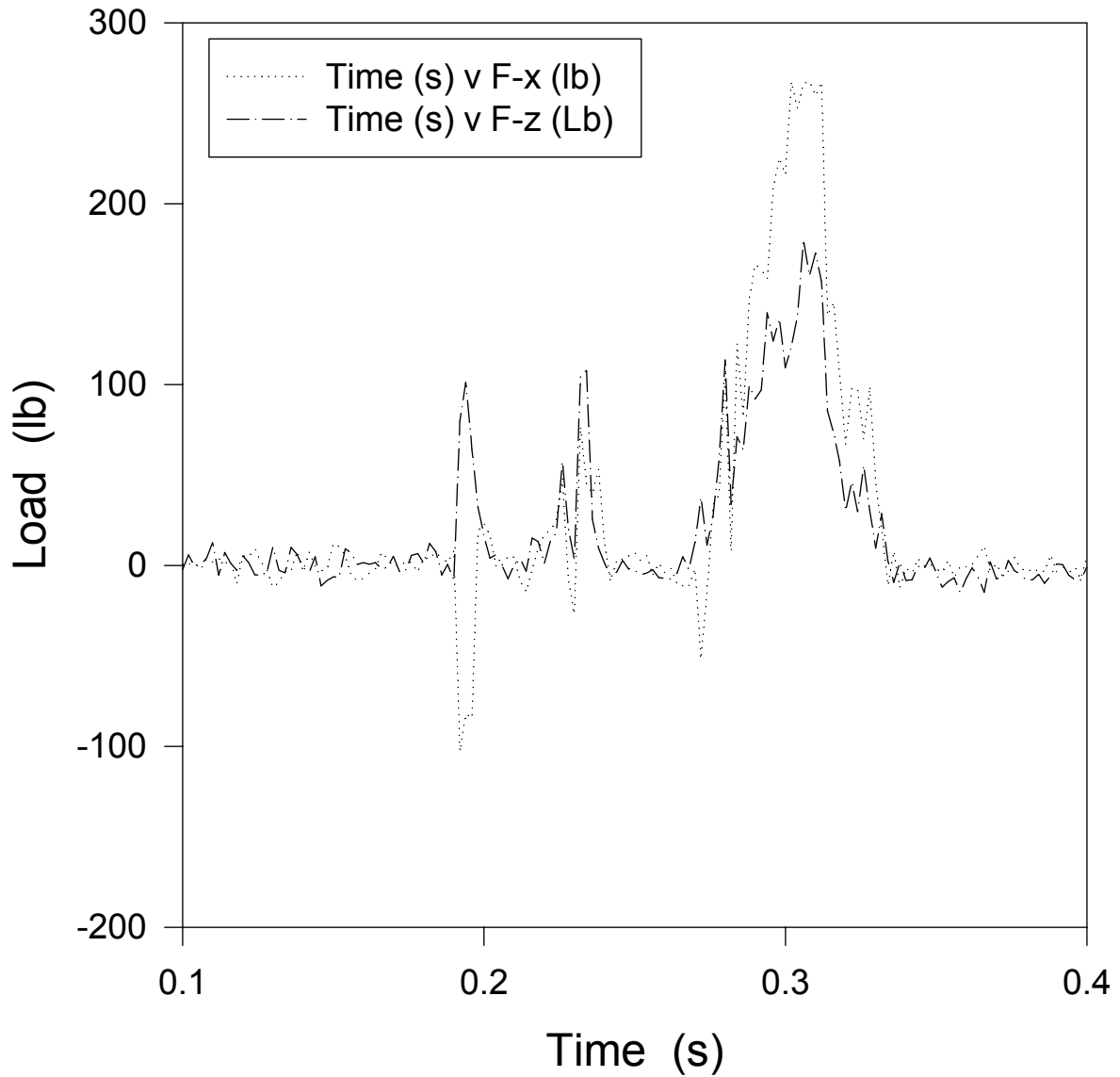


Figure A42: Sample DC-29 Load Trace  
Test: Unsuccessful  
Ice Type: Compacted Frozen Snow  
Test temperature: -20° C  
Horizontal Force:  $46 \pm 53$  lbs  
Vertical Force:  $58 \pm 92$  lbs



## DC-30

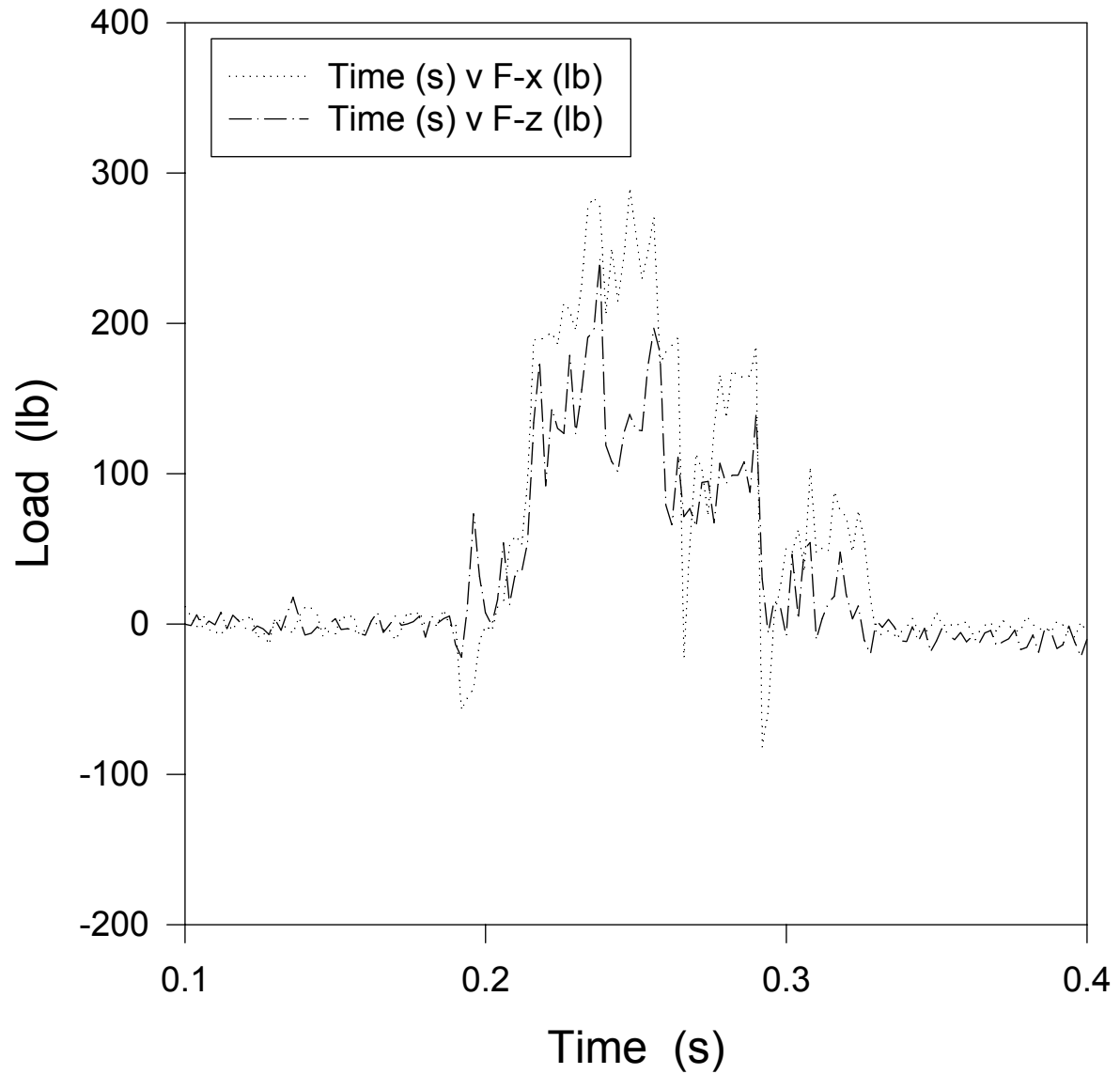


Figure A43: Sample DC-30 Load Trace  
Test: Successful  
Ice Type: Compacted Frozen Snow  
Test temperature: -20° C  
Horizontal Force:  $102 \pm 56$  lbs  
Vertical Force:  $145 \pm 100$  lbs

## DC-31

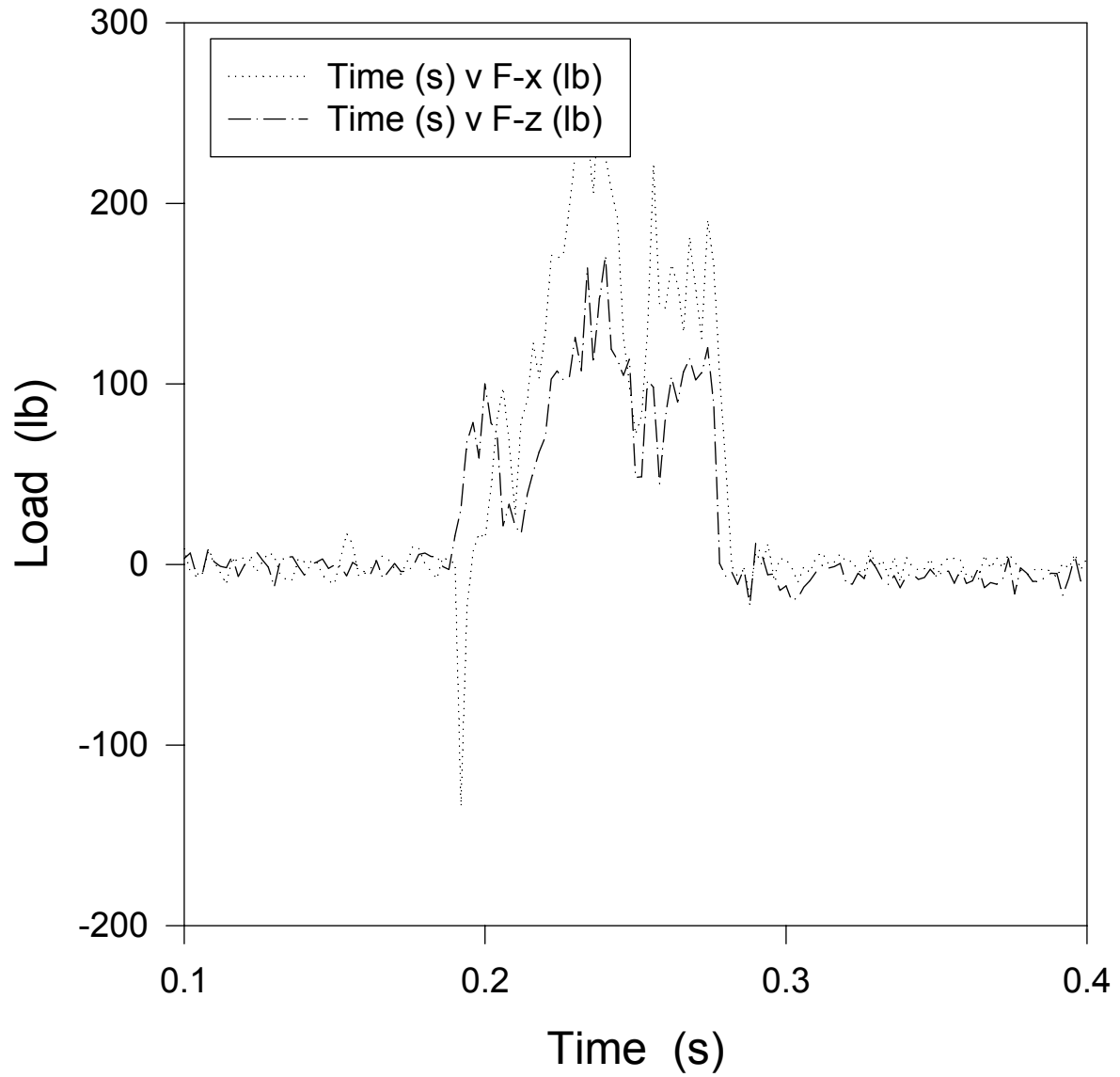


Figure A44: Sample DC-31 Load Trace  
Test: Successful  
Ice Type: Compacted Frozen Snow  
Test temperature: -20° C  
Horizontal Force:  $86 \pm 40$  lbs  
Vertical Force:  $126 \pm 83$  lbs

## DS-01

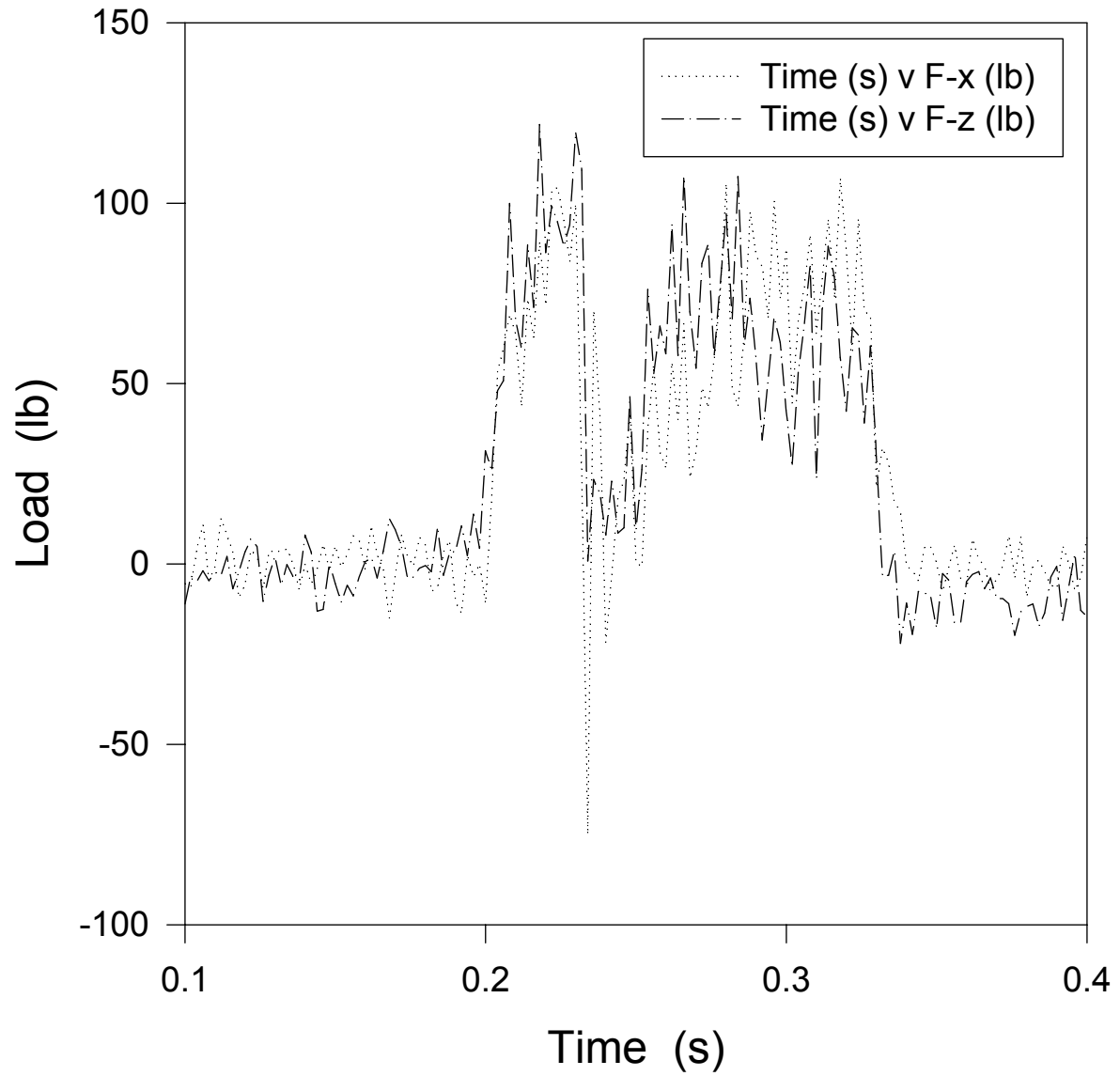


Figure A45: Sample DS-01 Load Trace

Test: Successful

Ice Type: Spray Ice

Test temperature:  $-1^{\circ}\text{C}$

Horizontal Force:  $60 \pm 30$  lbs

Vertical Force:  $56 \pm 35$  lbs

## DS-02

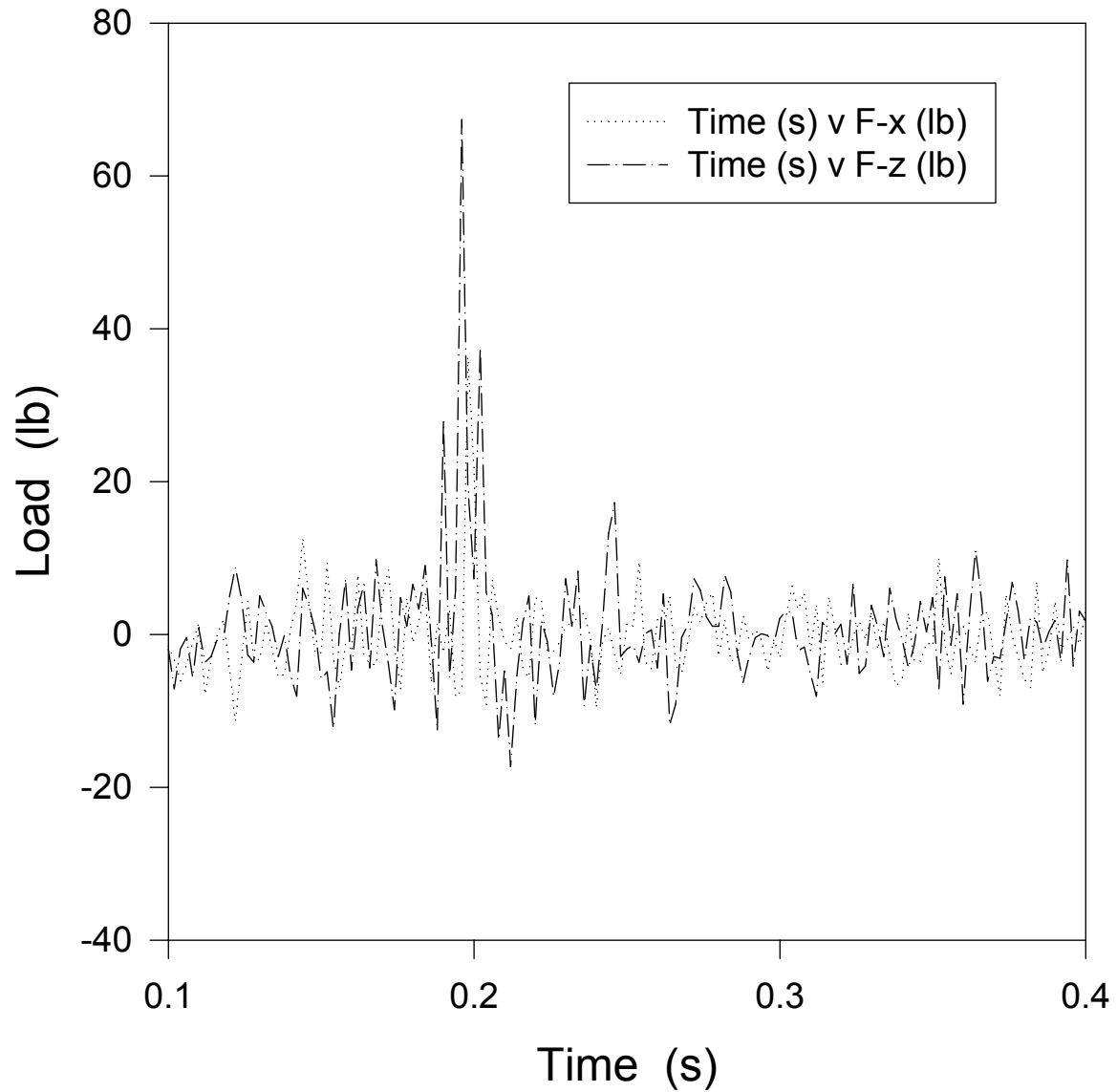


Figure A46: Sample DS-02 Load Trace

Test: Unsuccessful

Ice Type: Spray Ice

Test temperature:  $-1^{\circ}\text{C}$

Horizontal Force:  $2 \pm 13$  lbs

Vertical Force:  $1 \pm 8$  lbs

## DS-03

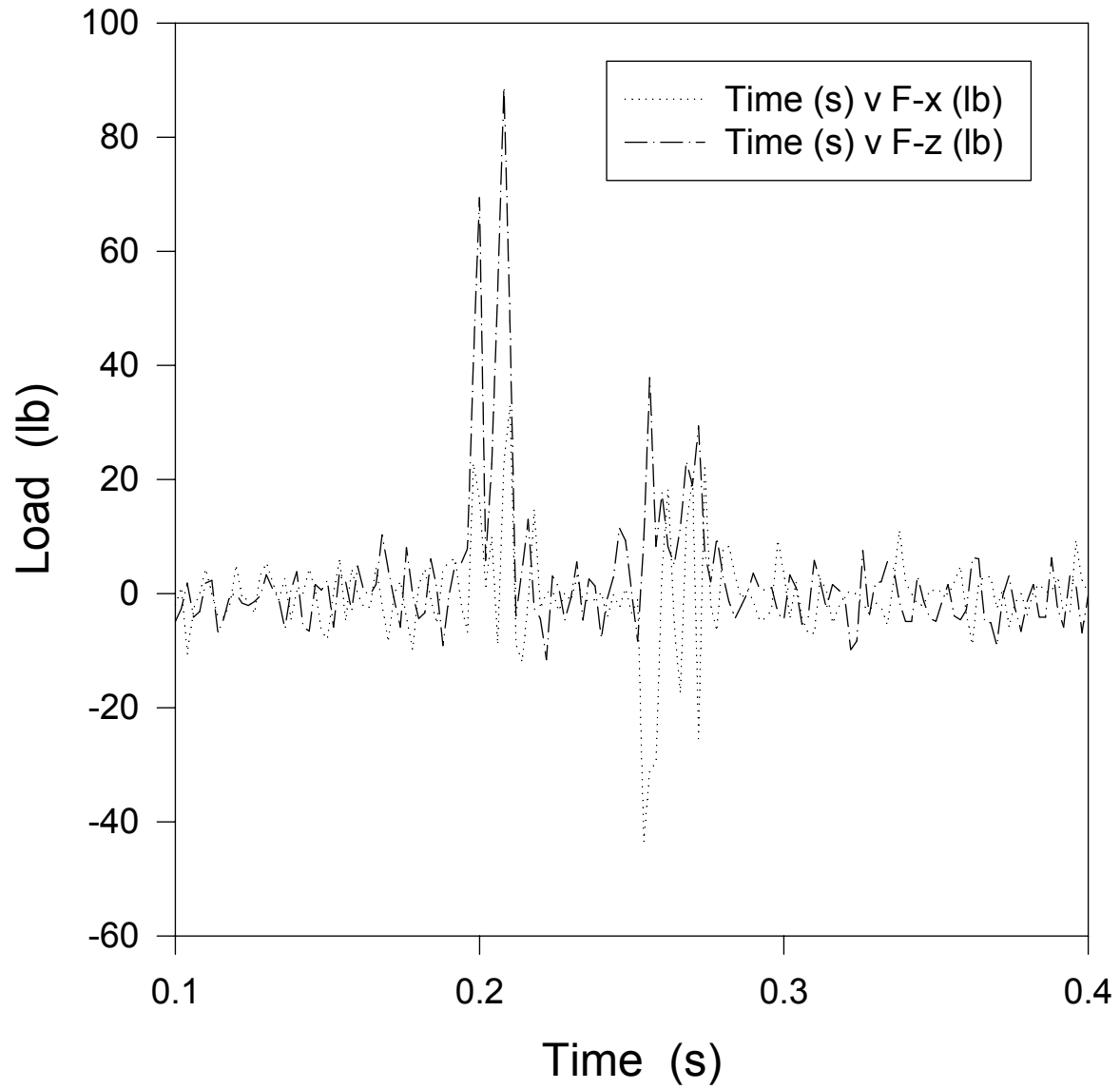


Figure A47: Sample DS-03 Load Trace

Test: Unsuccessful

Ice Type: Spray Ice

Test temperature:  $-1^{\circ}\text{C}$

Horizontal Force:  $28 \pm 29$  lbs

Vertical Force:  $6 \pm 14$  lbs

## DS-04

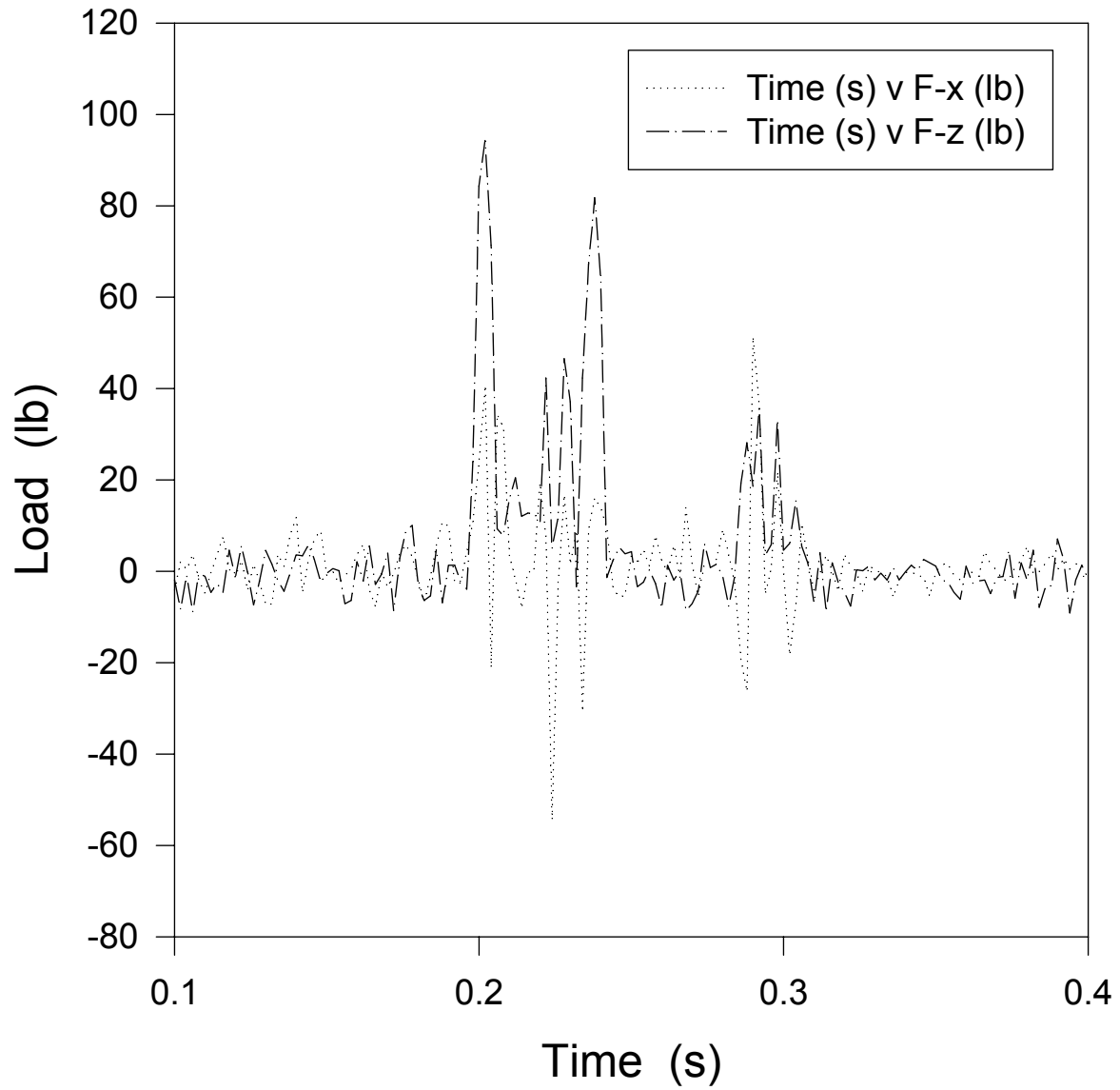


Figure A48: Sample DS-04 Load Trace

Test: Unsuccessful

Ice Type: Spray Ice

Test temperature:  $-1^{\circ}\text{C}$

Horizontal Force:  $16 \pm 25$  lbs

Vertical Force:  $4 \pm 17$  lbs

## DS-05

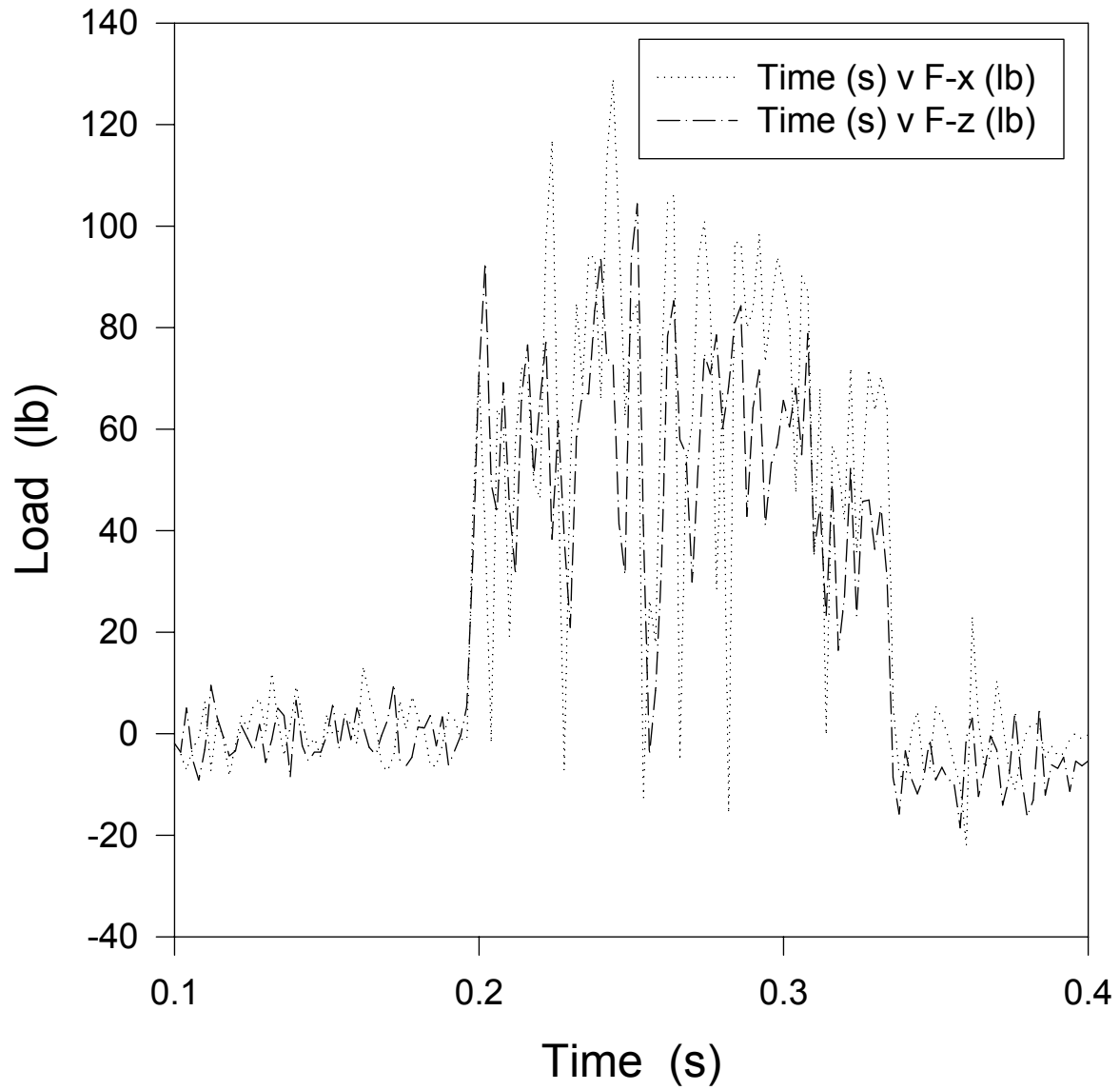


Figure A49: Sample DS-05 Load Trace

Test: Successful

Ice Type: Spray Ice

Test temperature:  $-1^{\circ}\text{C}$

Horizontal Force:  $55 \pm 22$  lbs

Vertical Force:  $64 \pm 32$  lbs

## DS-06

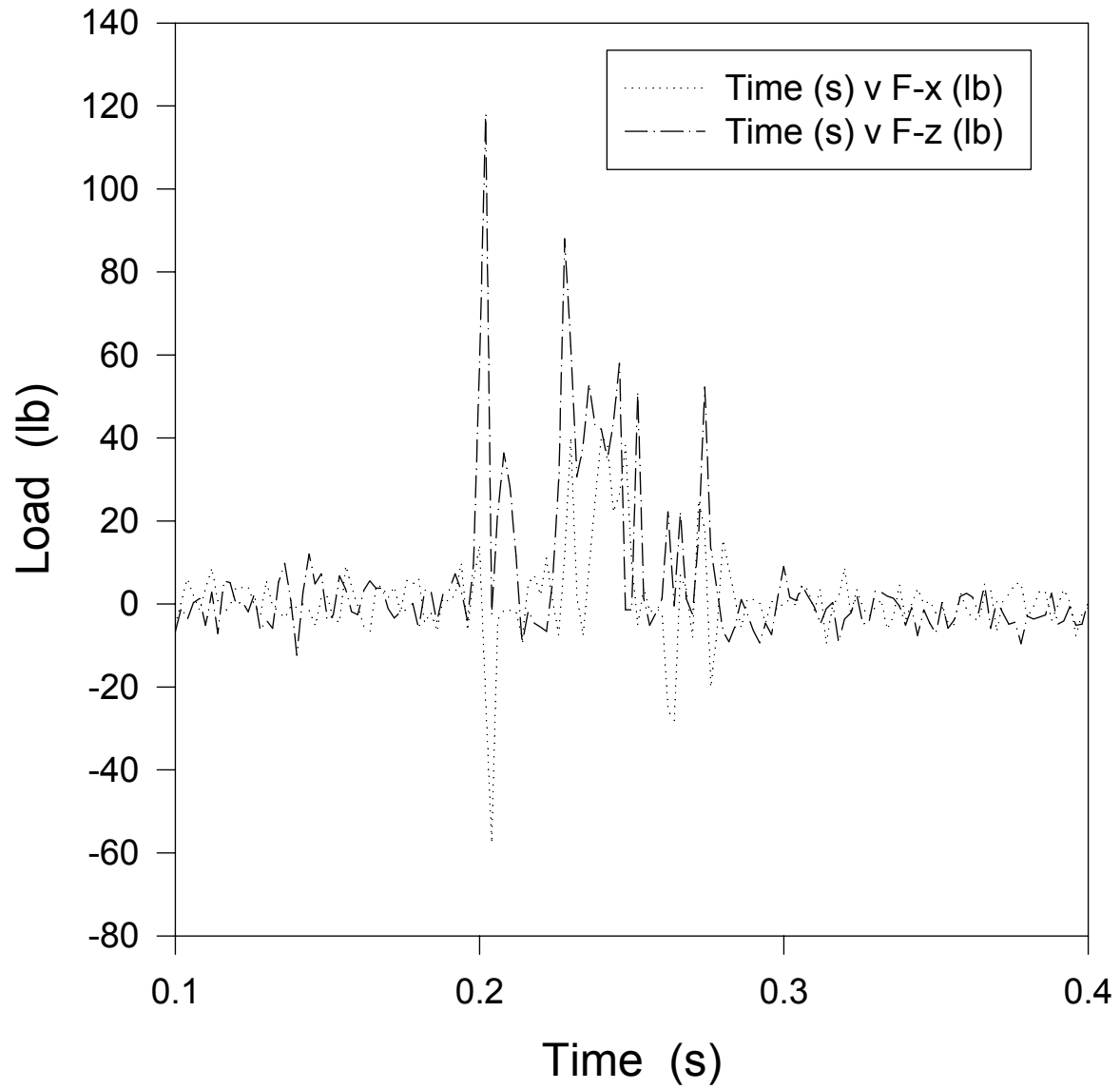


Figure A50: Sample DS-06 Load Trace

Test: Unsuccessful

Ice Type: Spray Ice

Test temperature: -1° C

Horizontal Force:  $16 \pm 27$  lbs

Vertical Force:  $3 \pm 17$  lbs



## DS-13

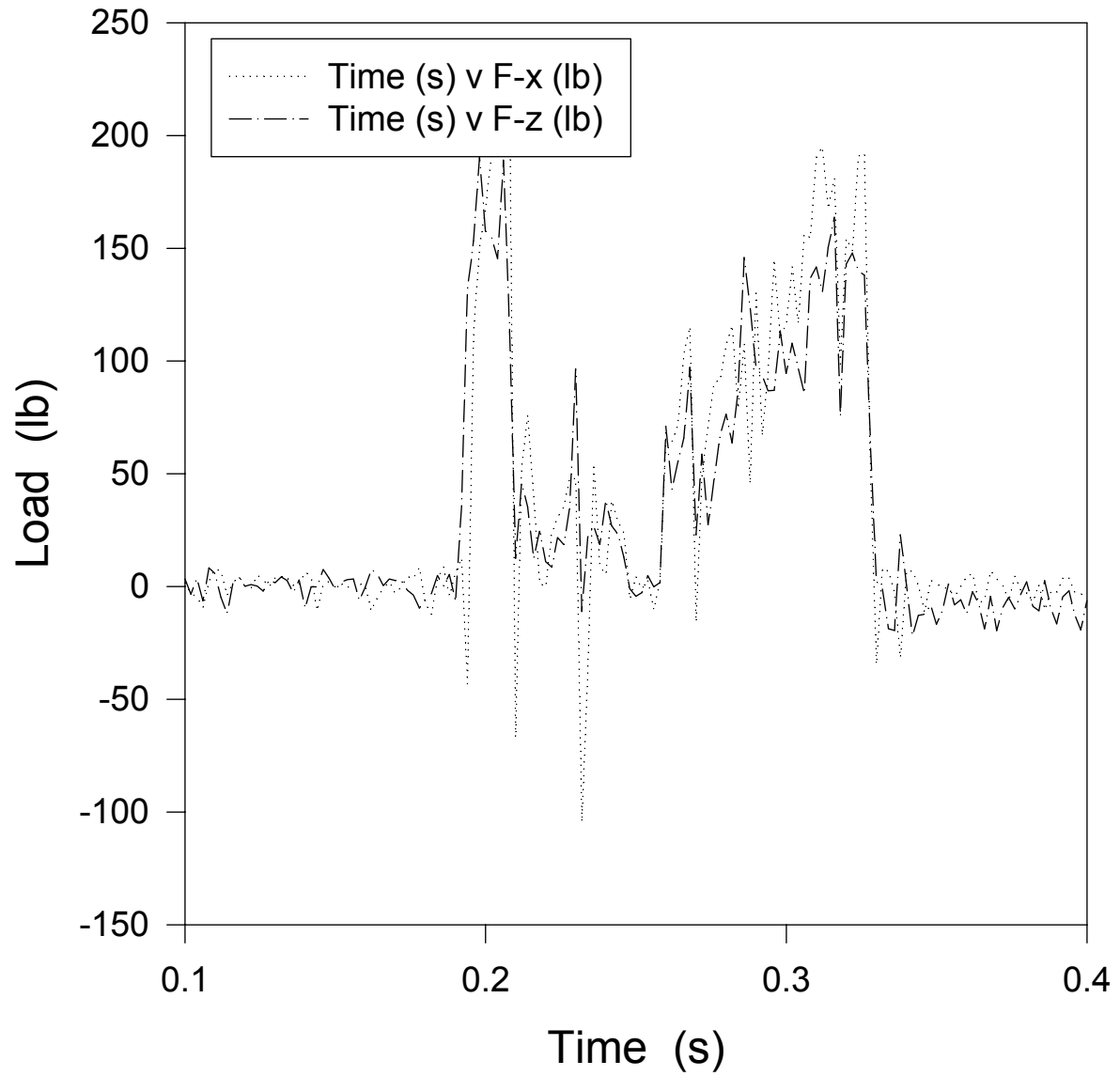


Figure A51: Sample DS-13 Load Trace

Test: Successful

Ice Type: Spray Ice

Test temperature:  $-5^{\circ}\text{C}$

Horizontal Force:  $74 \pm 55$  lbs

Vertical Force:  $78 \pm 74$  lbs

## DS-14

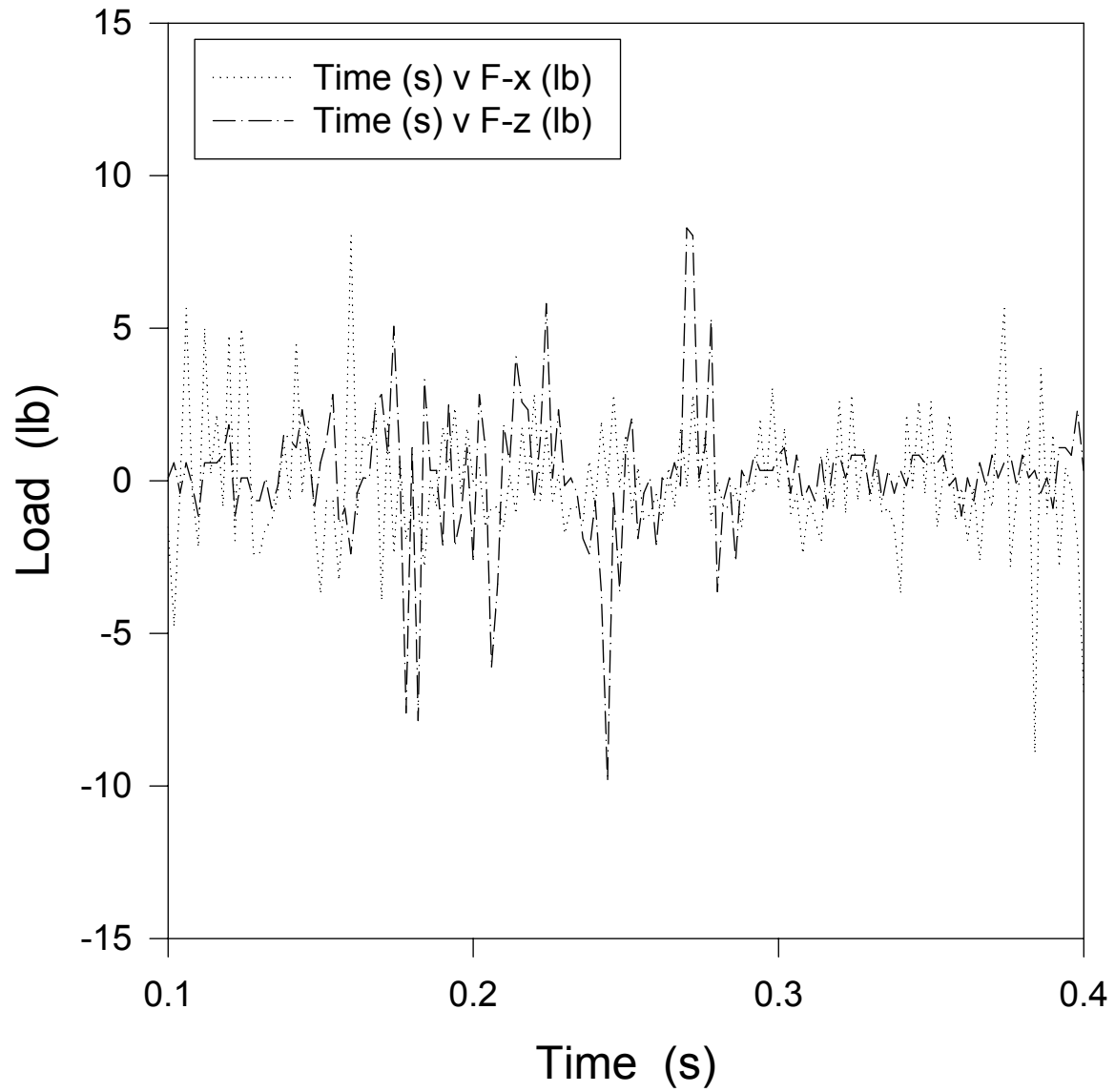


Figure A52: Sample DS-14 Load Trace

Test: Unsuccessful

Ice Type: Spray Ice

Test temperature:  $-5^{\circ}\text{C}$

Horizontal Force:  $0 \pm 3$  lbs

Vertical Force:  $0 \pm 1$  lbs

## DS-15

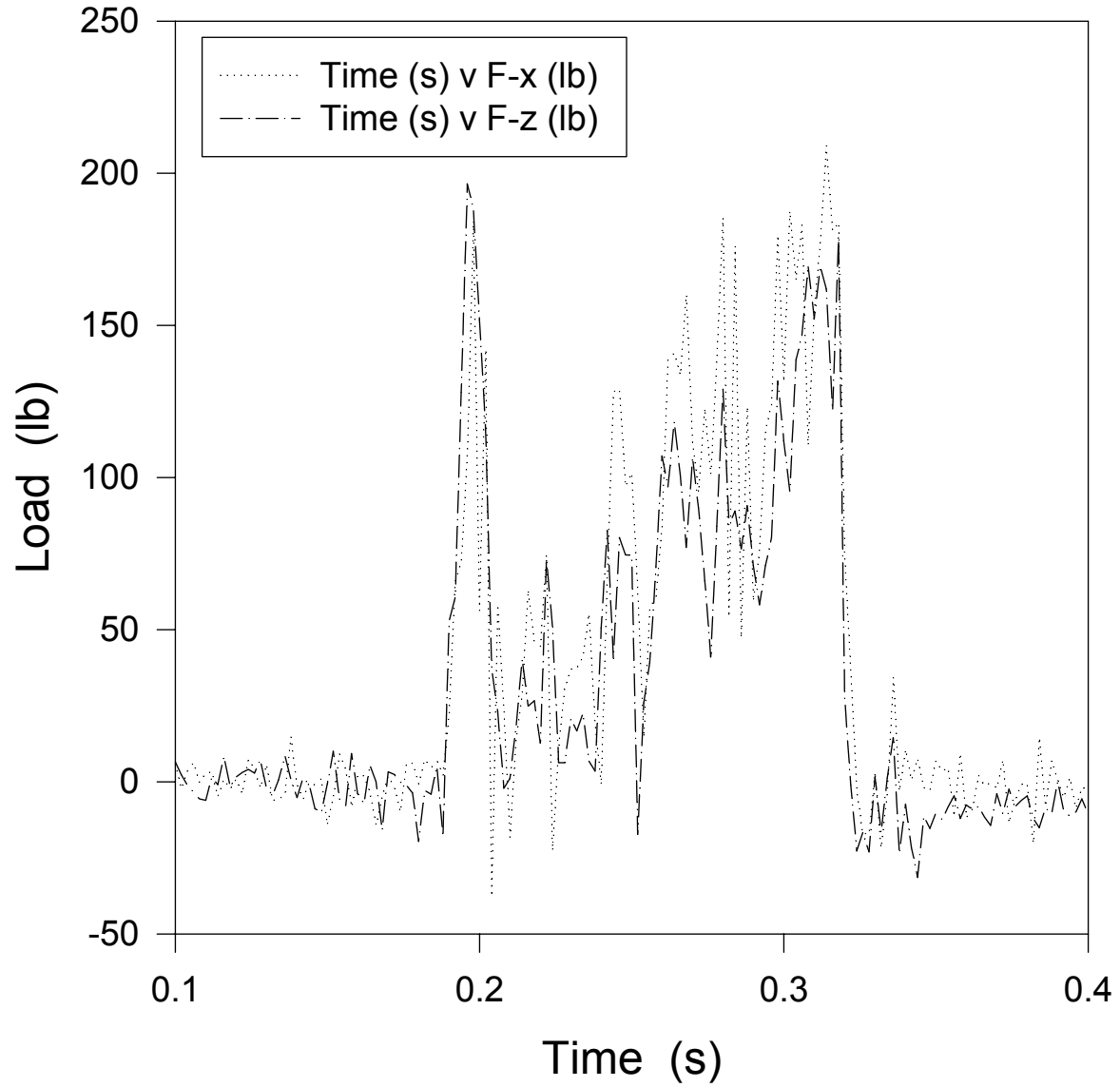


Figure A53: Sample DS-15 Load Trace

Test: Successful

Ice Type: Spray Ice

Test temperature:  $-5^{\circ}\text{C}$

Horizontal Force:  $77 \pm 53$  lbs

Vertical Force:  $91 \pm 61$  lbs

## DS-16

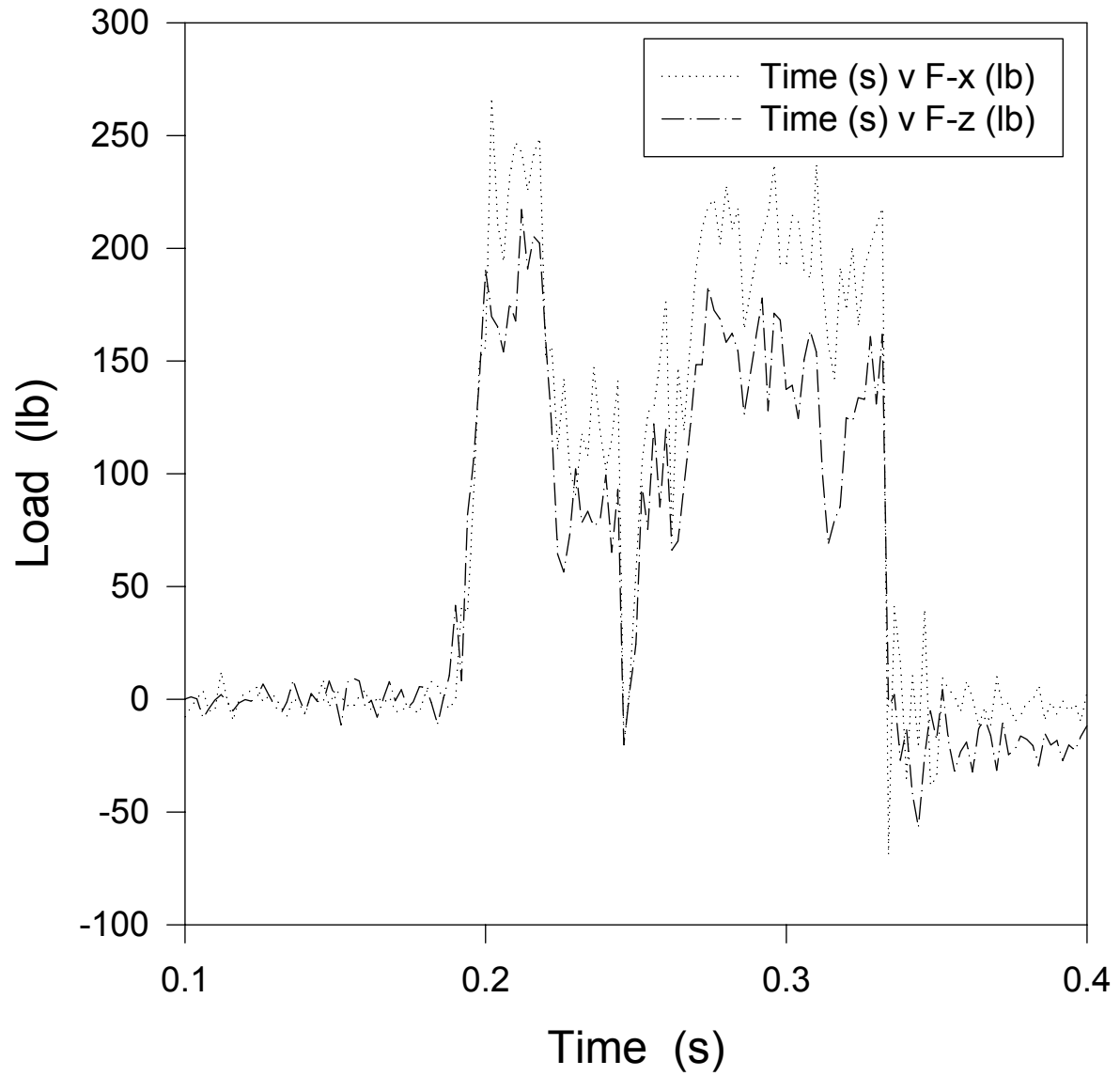


Figure A54: Sample DS-16 Load Trace

Test: Successful

Ice Type: Spray Ice

Test temperature:  $-5^{\circ}\text{C}$

Horizontal Force:  $120 \pm 52$  lbs

Vertical Force:  $161 \pm 65$  lbs

## DS-17

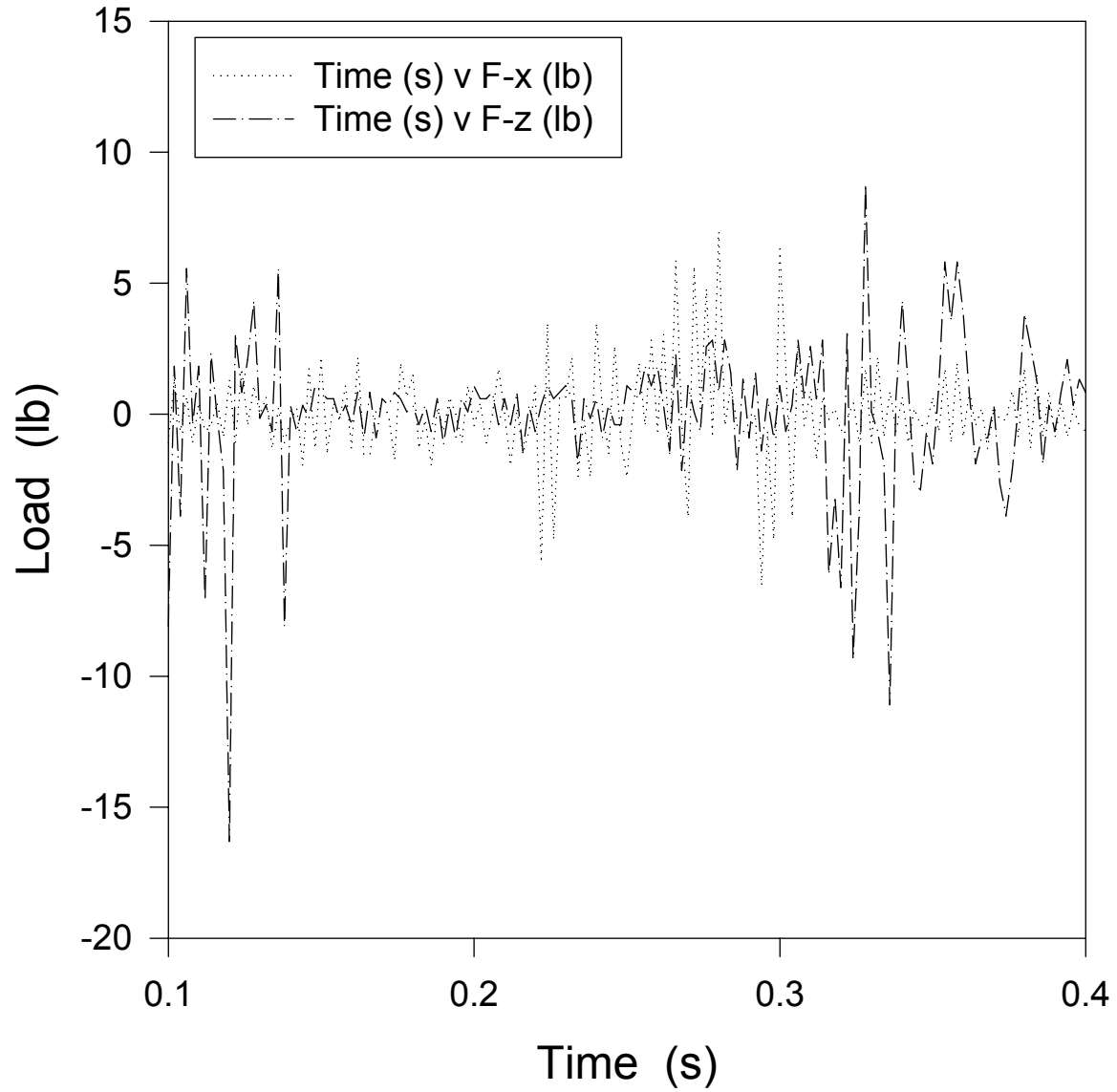


Figure A55: Sample DS-17 Load Trace

Test: Unsuccessful

Ice Type: Spray Ice

Test temperature: -5° C

Horizontal Force:  $0 \pm 2$  lbs

Vertical Force:  $0 \pm 3$  lbs

## DS-18

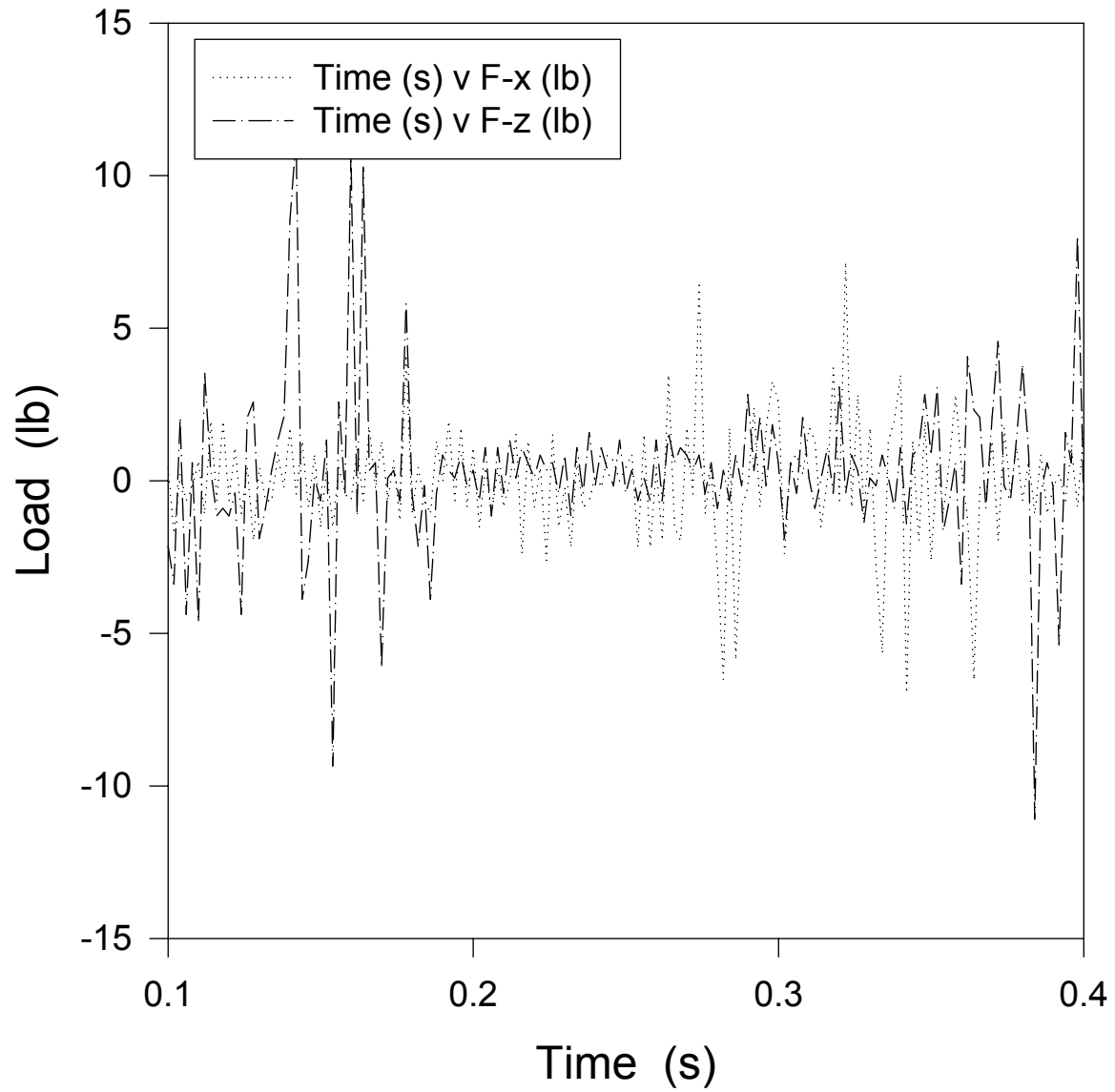


Figure A56: Sample DS-18 Load Trace

Test: Unsuccessful

Ice Type: Spray Ice

Test temperature:  $-5^{\circ}\text{C}$

Horizontal Force:  $0 \pm 1$  lbs

Vertical Force:  $0 \pm 2$  lbs

## DS-19

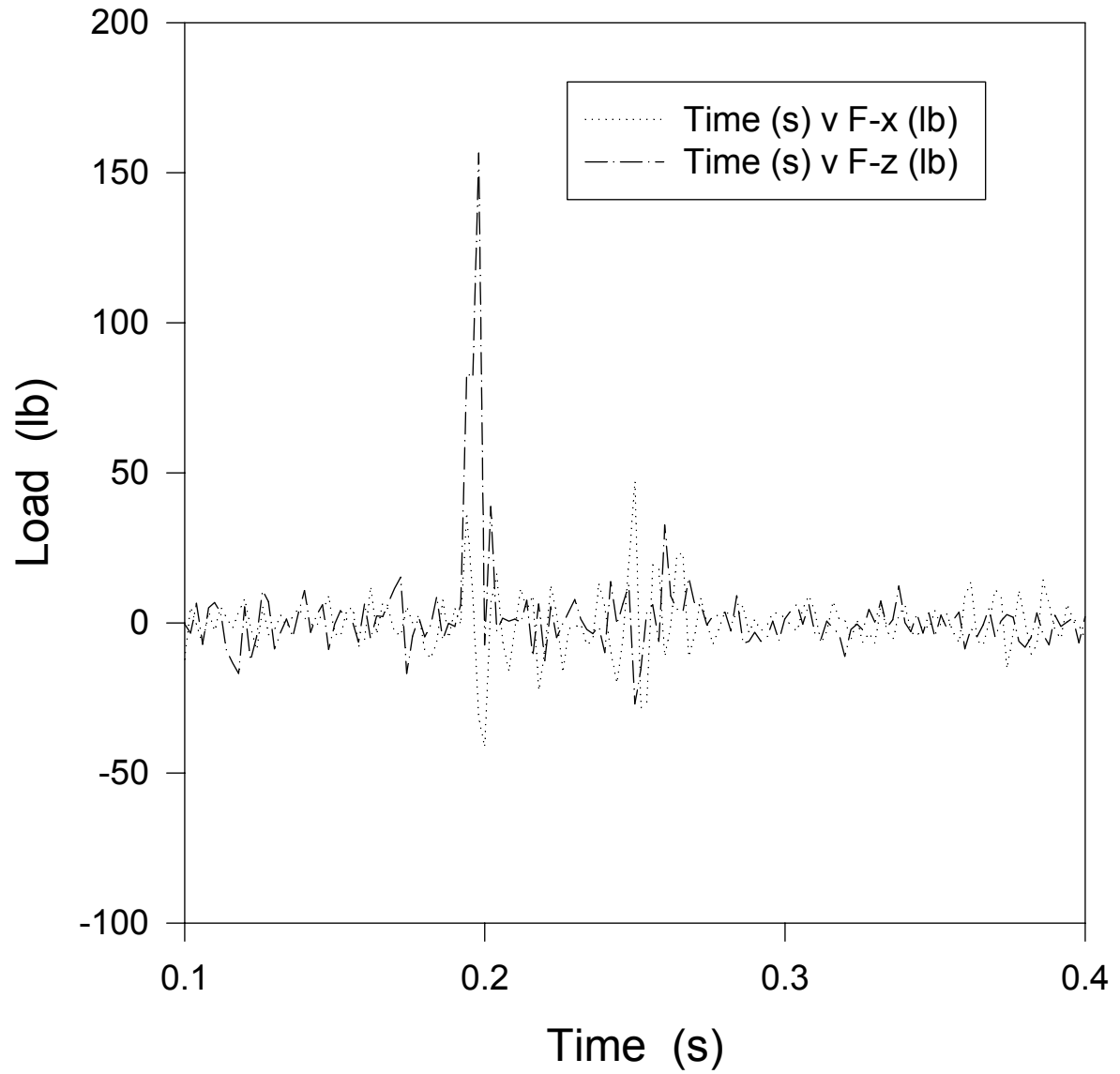


Figure A57: Sample DS-19 Load Trace

Test: Unsuccessful

Ice Type: Spray Ice

Test temperature:  $-5^{\circ}\text{C}$

Horizontal Force:  $60 \pm 60$  lbs

Vertical Force:  $-4 \pm 29$  lbs

## DS-20

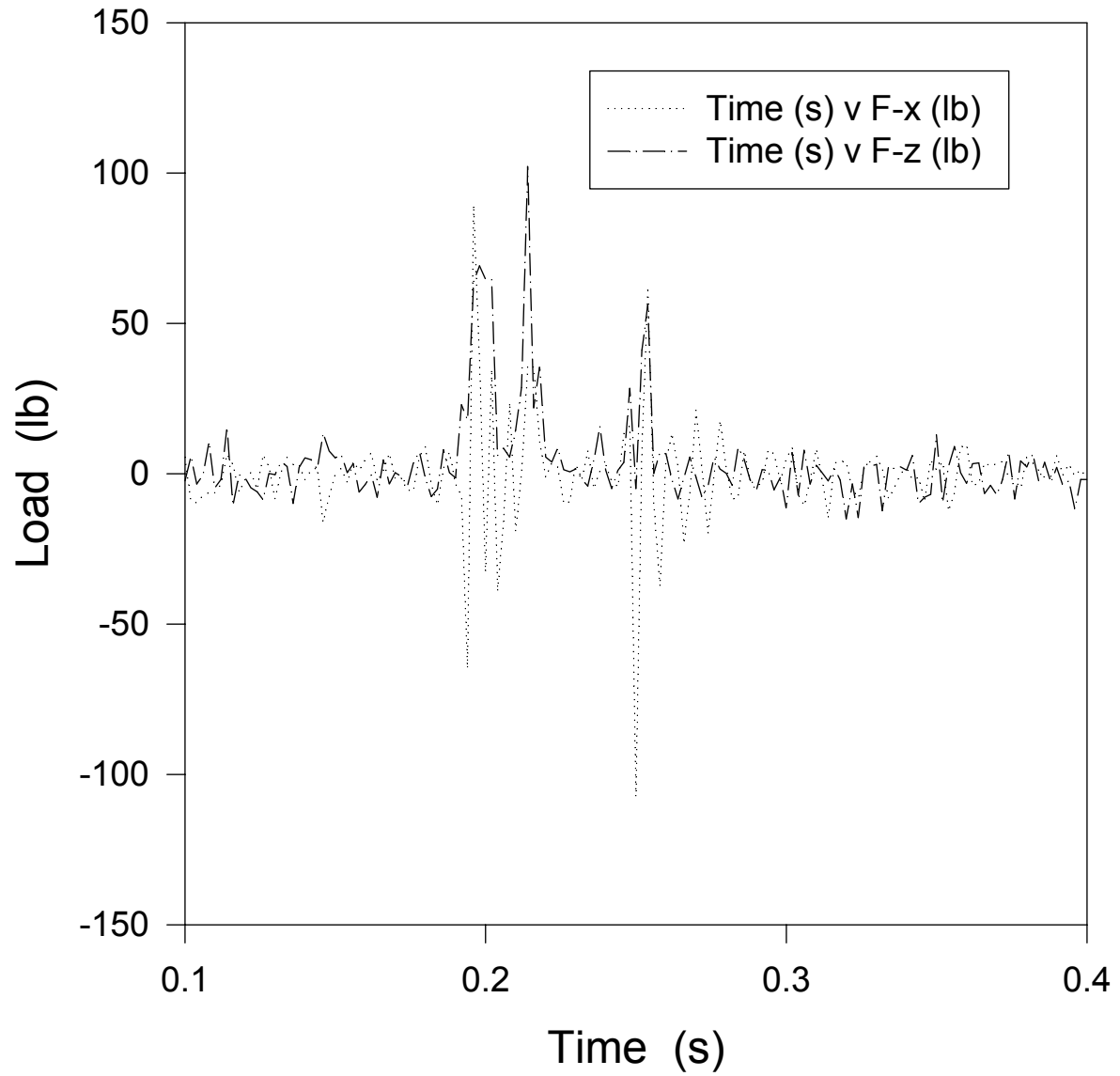


Figure A58: Sample DS-20 Load Trace  
Test: Unsuccessful  
Ice Type: Spray Ice  
Test temperature:  $-5^{\circ}\text{C}$   
Horizontal Force:  $20 \pm 26$  lbs  
Vertical Force:  $1 \pm 34$  lbs



## DS-21

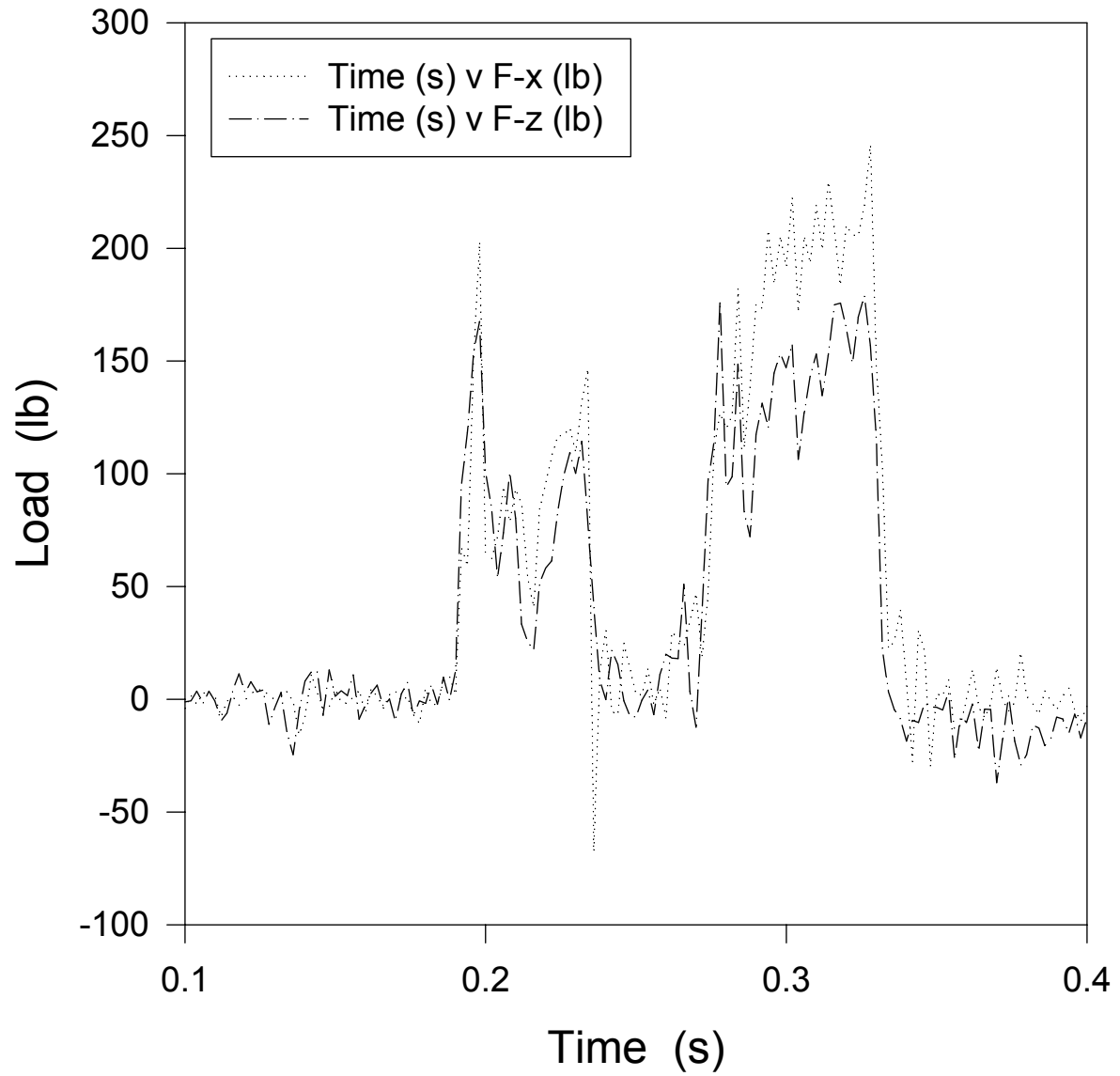


Figure A59: Sample DS-21 Load Trace

Test: Successful

Ice Type: Spray Ice

Test temperature:  $-5^{\circ}\text{C}$

Horizontal Force:  $83 \pm 59$  lbs

Vertical Force:  $105 \pm 78$  lbs

## DS-22

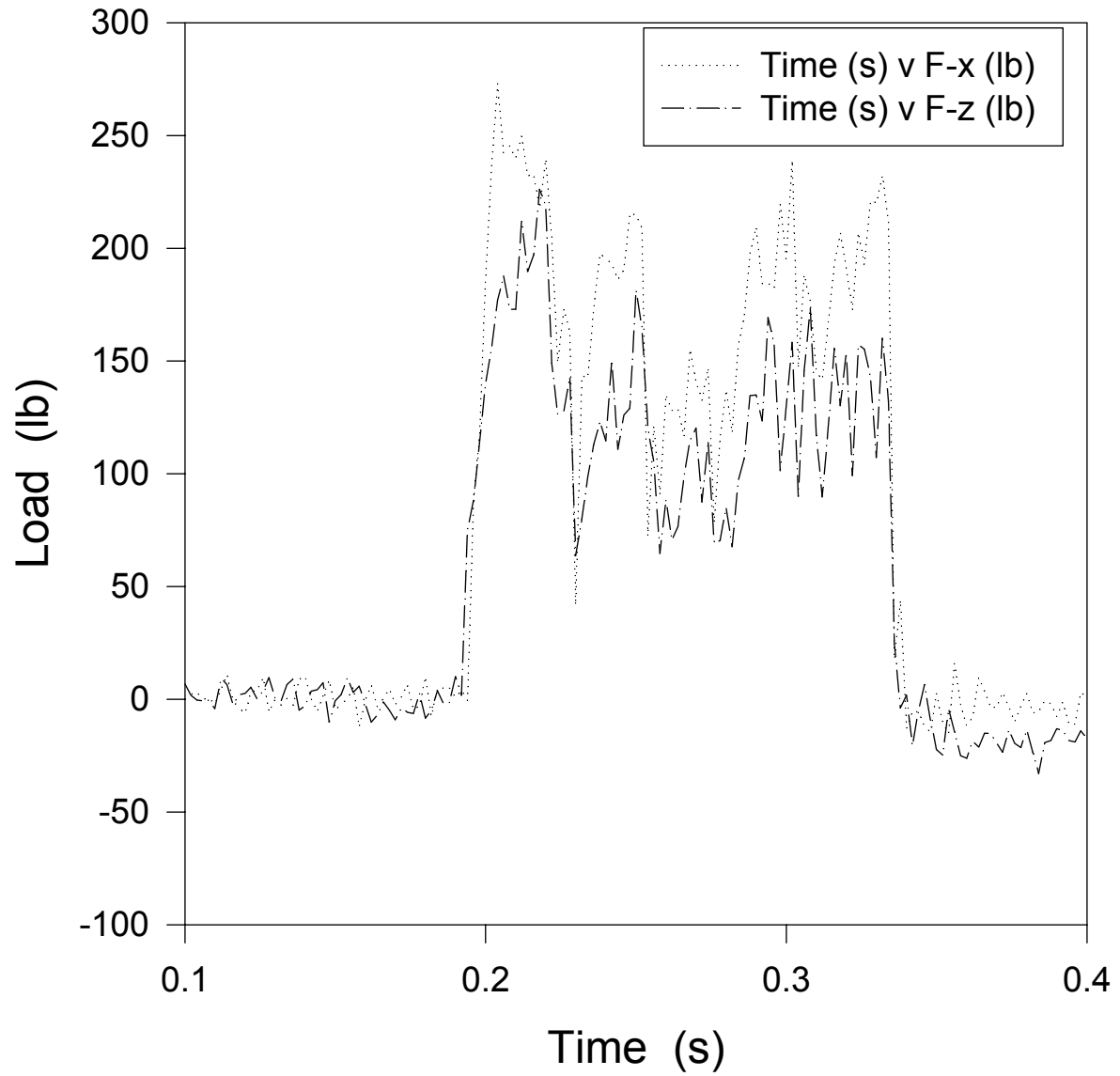


Figure A60: Sample DS-22 Load Trace

Test: Successful

Ice Type: Spray Ice

Test temperature: -5° C

Horizontal Force:  $127 \pm 41$  lbs

Vertical Force:  $172 \pm 55$  lbs

## DS-23

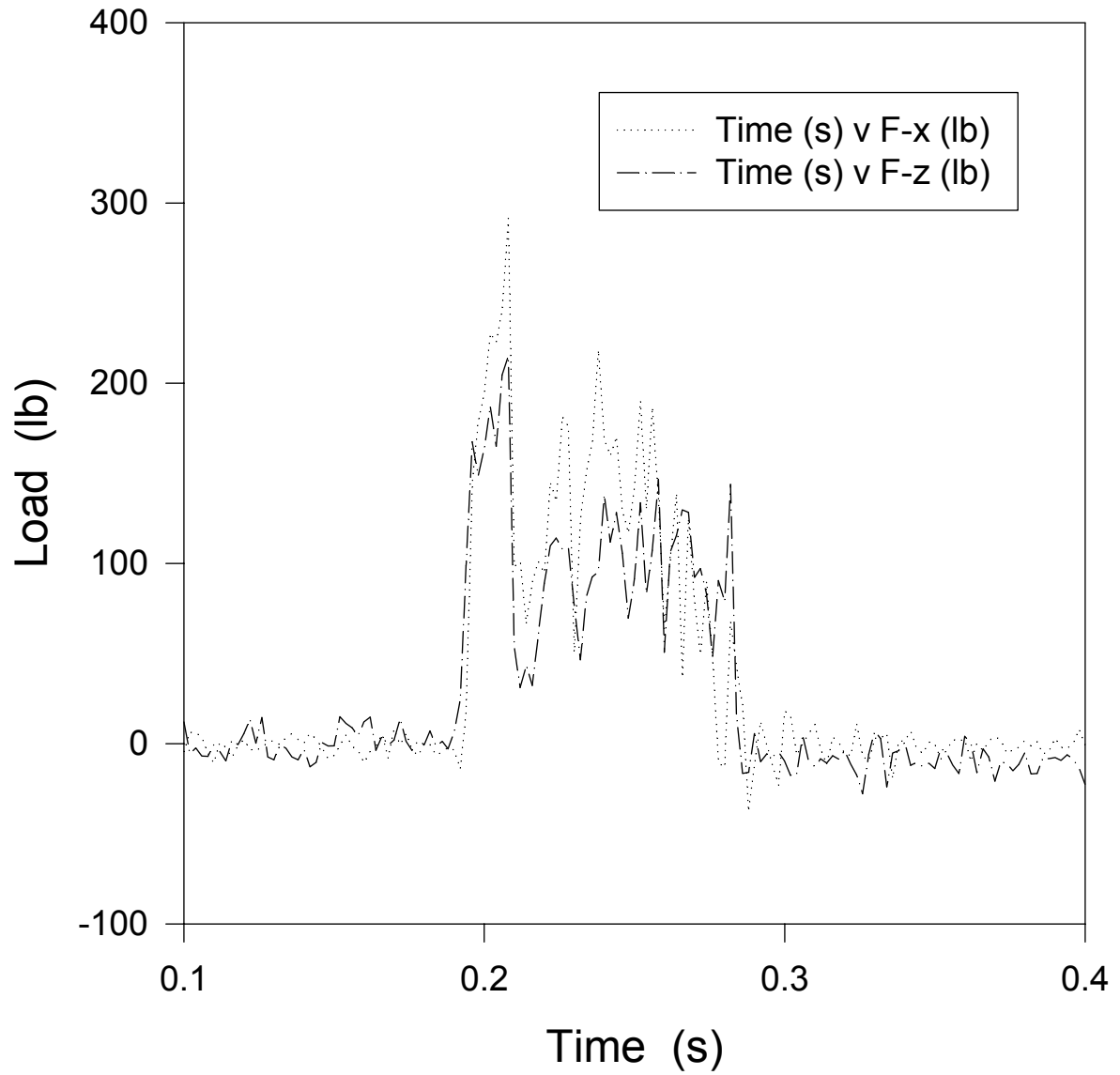


Figure A61: Sample DS-23 Load Trace

Test: Successful

Ice Type: Spray Ice

Test temperature:  $-5^{\circ}\text{C}$

Horizontal Force:  $104 \pm 45$  lbs

Vertical Force:  $125 \pm 67$  lbs

## DS-24

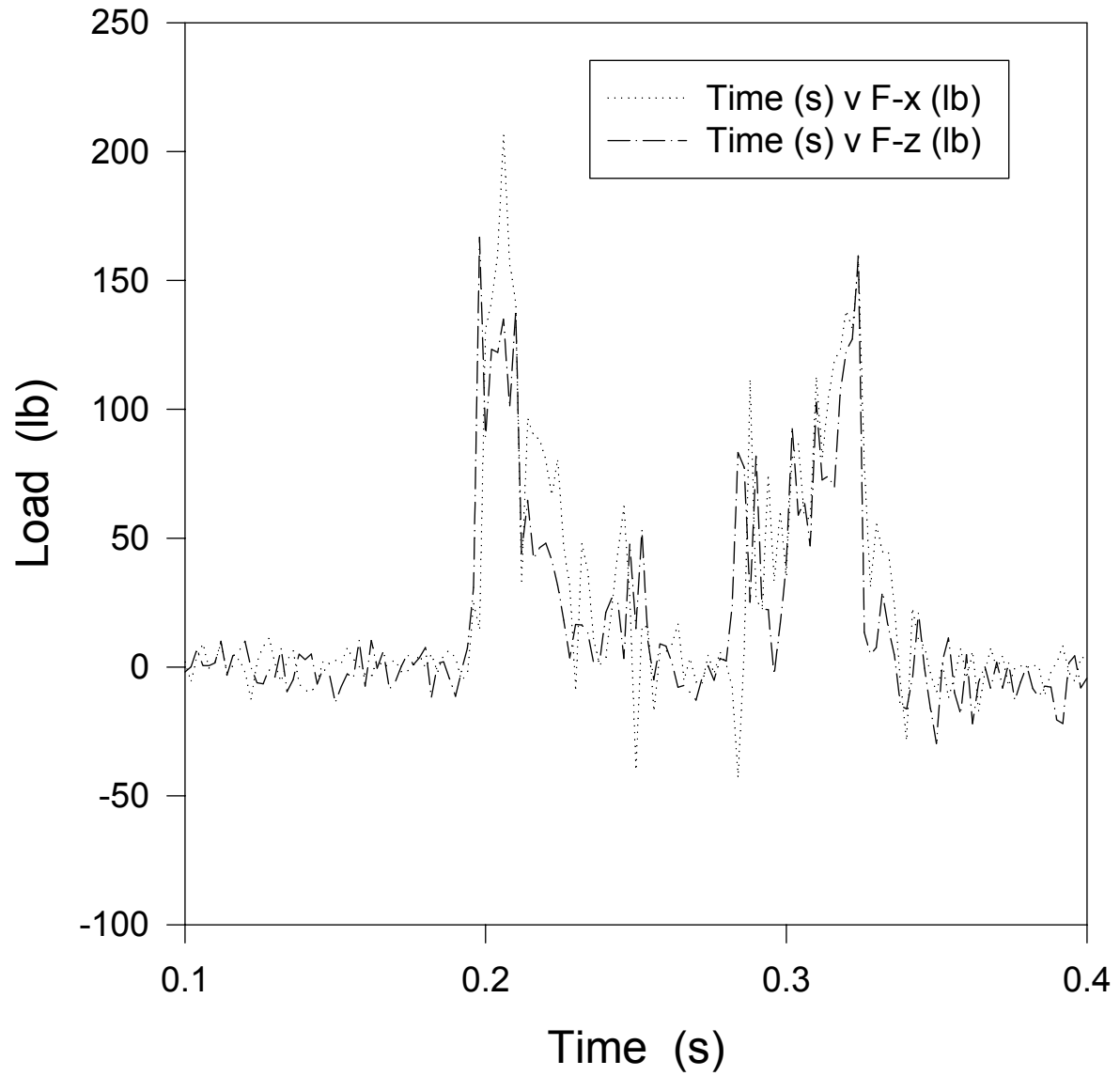


Figure A62: Sample DS-24 Load Trace

Test: Unsuccessful

Ice Type: Spray Ice

Test temperature:  $-5^{\circ}\text{C}$

Horizontal Force:  $43 \pm 46$  lbs

Vertical Force:  $52 \pm 54$  lbs

## DS-25

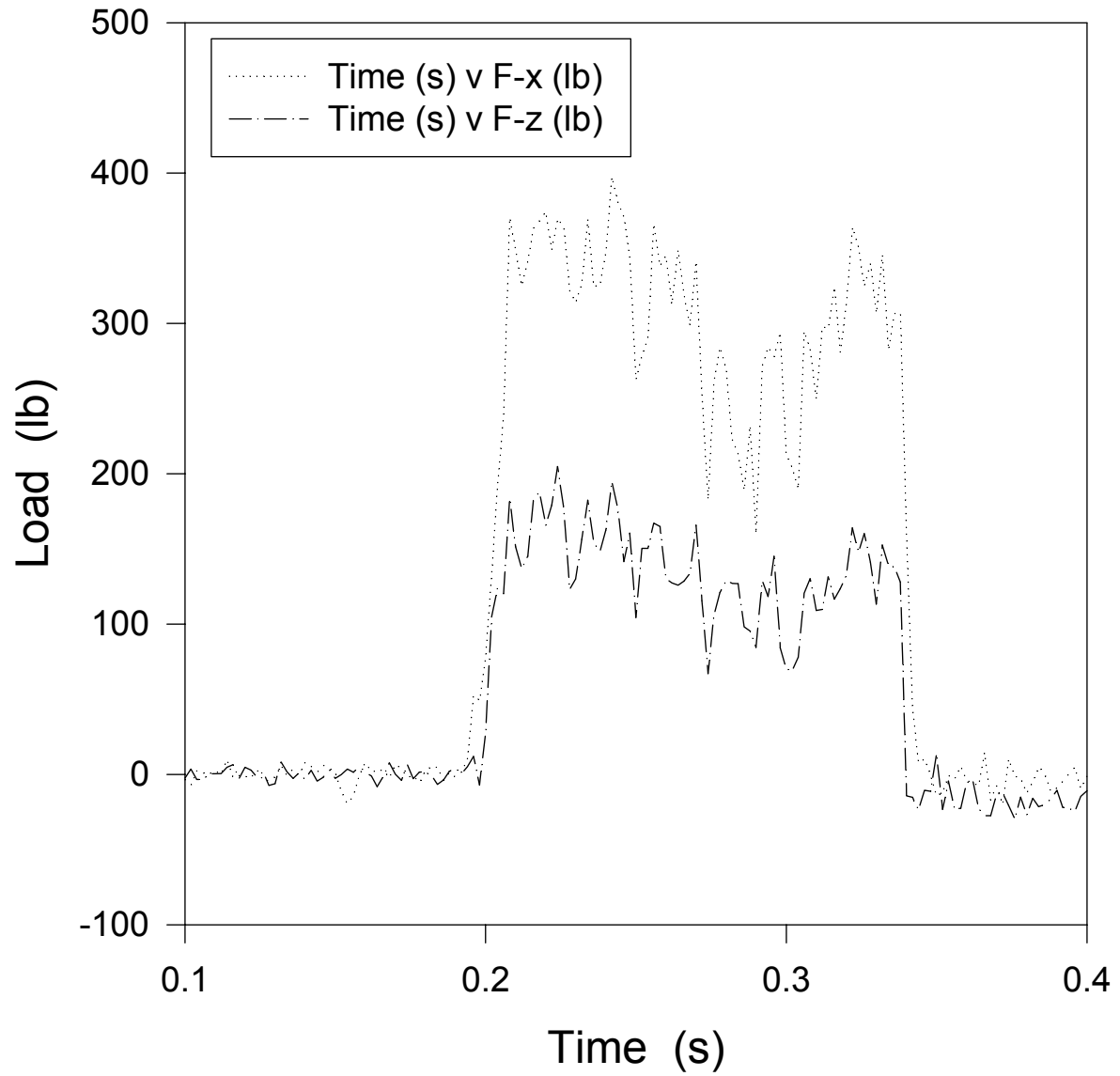


Figure A63: Sample DS-25 Load Trace

Test: Successful

Ice Type: Spray Ice

Test temperature: -20° C

Horizontal Force:  $134 \pm 33$  lbs

Vertical Force:  $297 \pm 65$  lbs

## DS-26

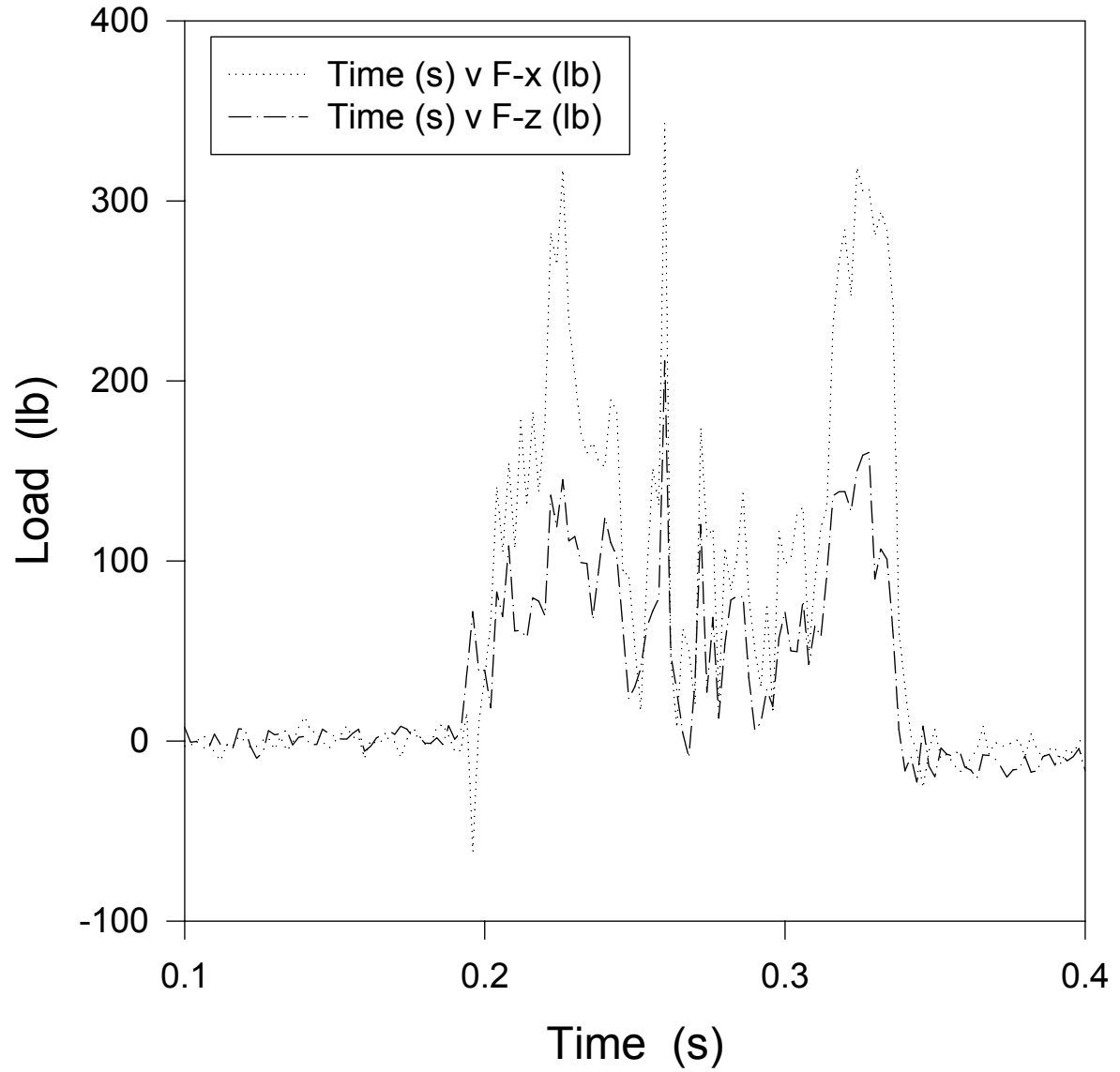


Figure A64: Sample DS-26 Load Trace

Test: Successful

Ice Type: Spray Ice

Test temperature: -20° C

Horizontal Force:  $76 \pm 44$  lbs

Vertical Force:  $141 \pm 93$  lbs

## DS-27

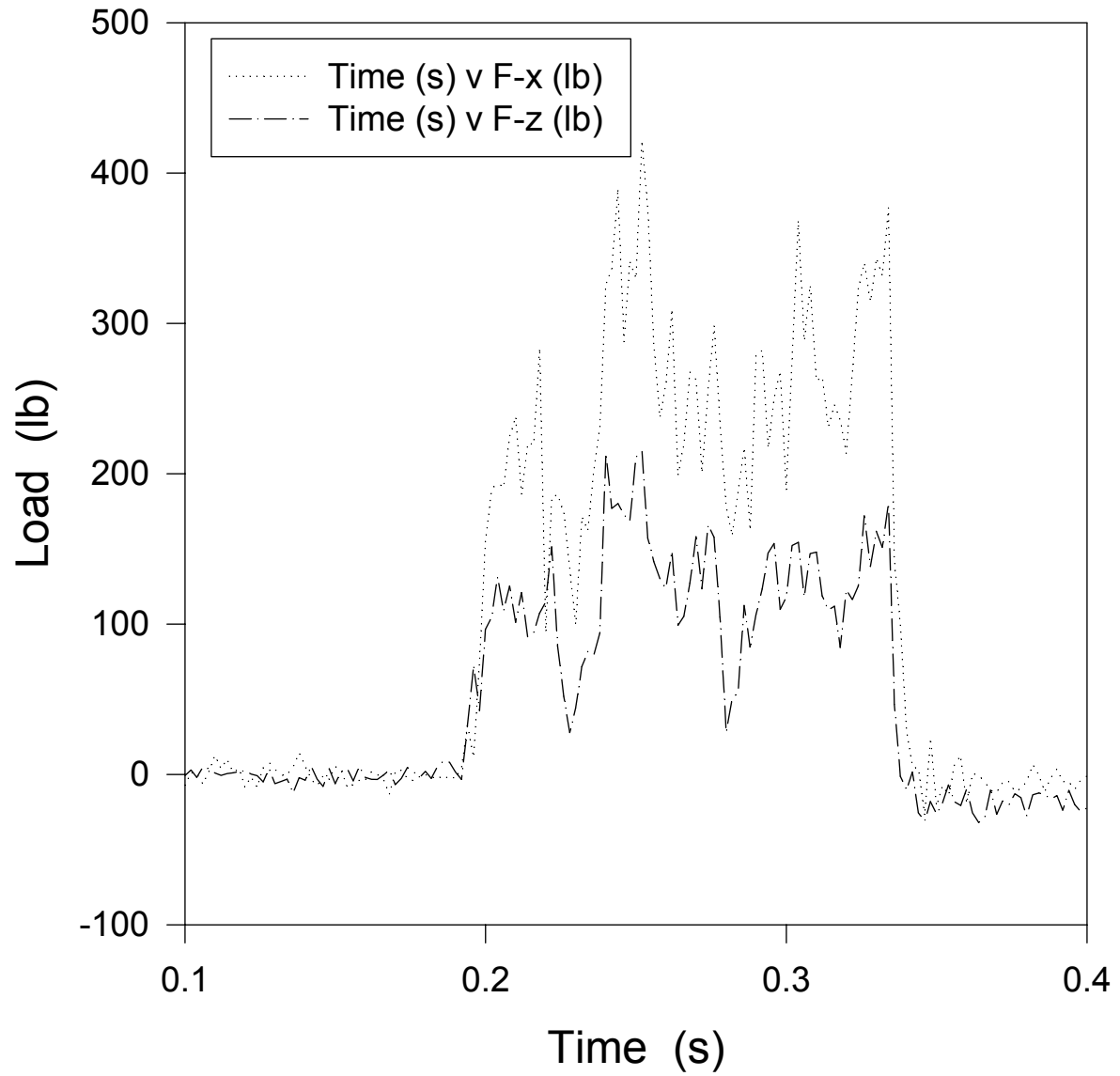


Figure A65: Sample DS-27 Load Trace

Test: Successful

Ice Type: Spray Ice

Test temperature: -20° C

Horizontal Force:  $119 \pm 43$  lbs

Vertical Force:  $240 \pm 81$  lbs

## DS-28

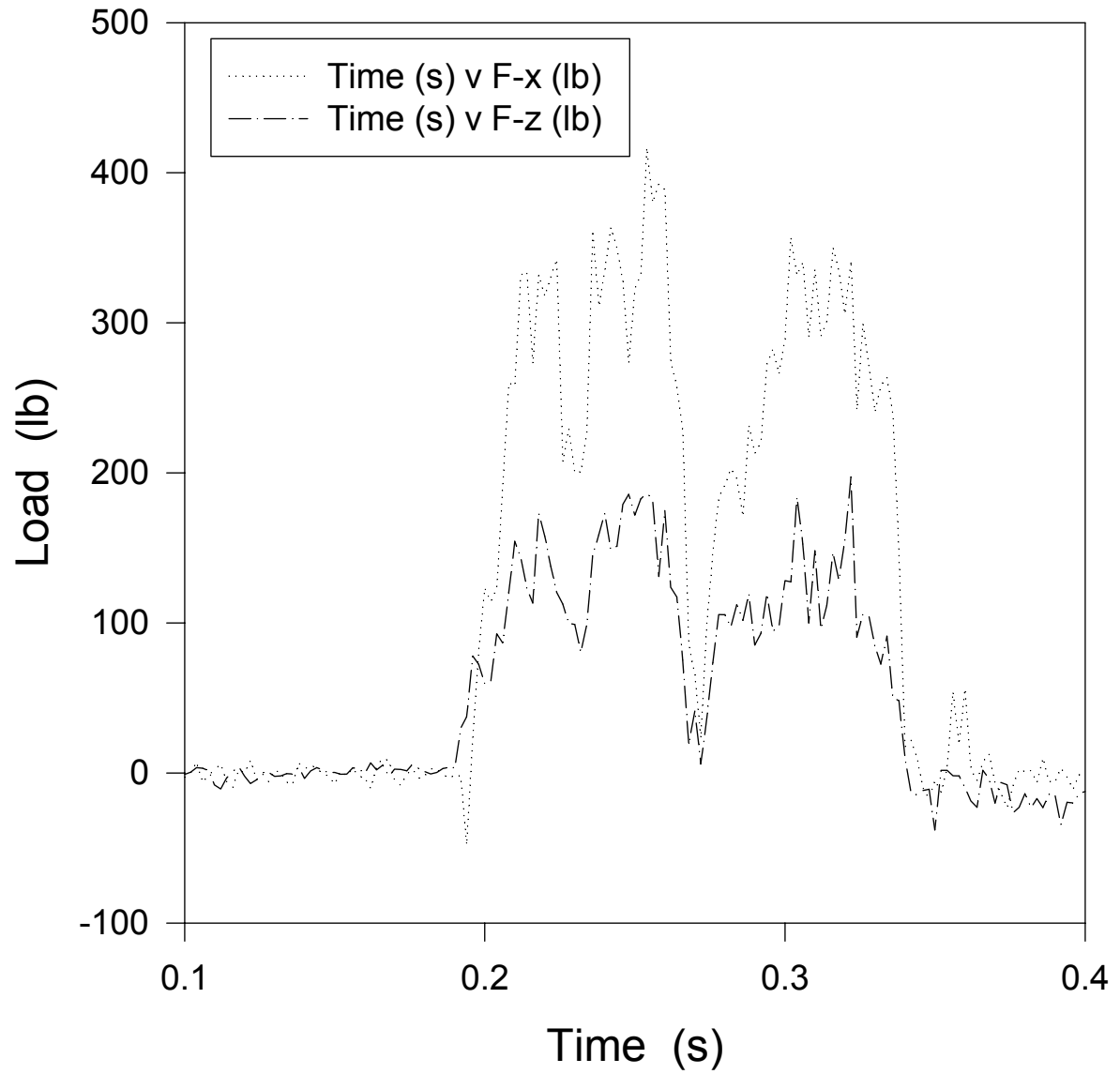


Figure A66: Sample DS-28 Load Trace

Test: Successful

Ice Type: Spray Ice

Test temperature: -20° C

Horizontal Force:  $114 \pm 44$  lbs

Vertical Force:  $254 \pm 94$  lbs



## DS-29

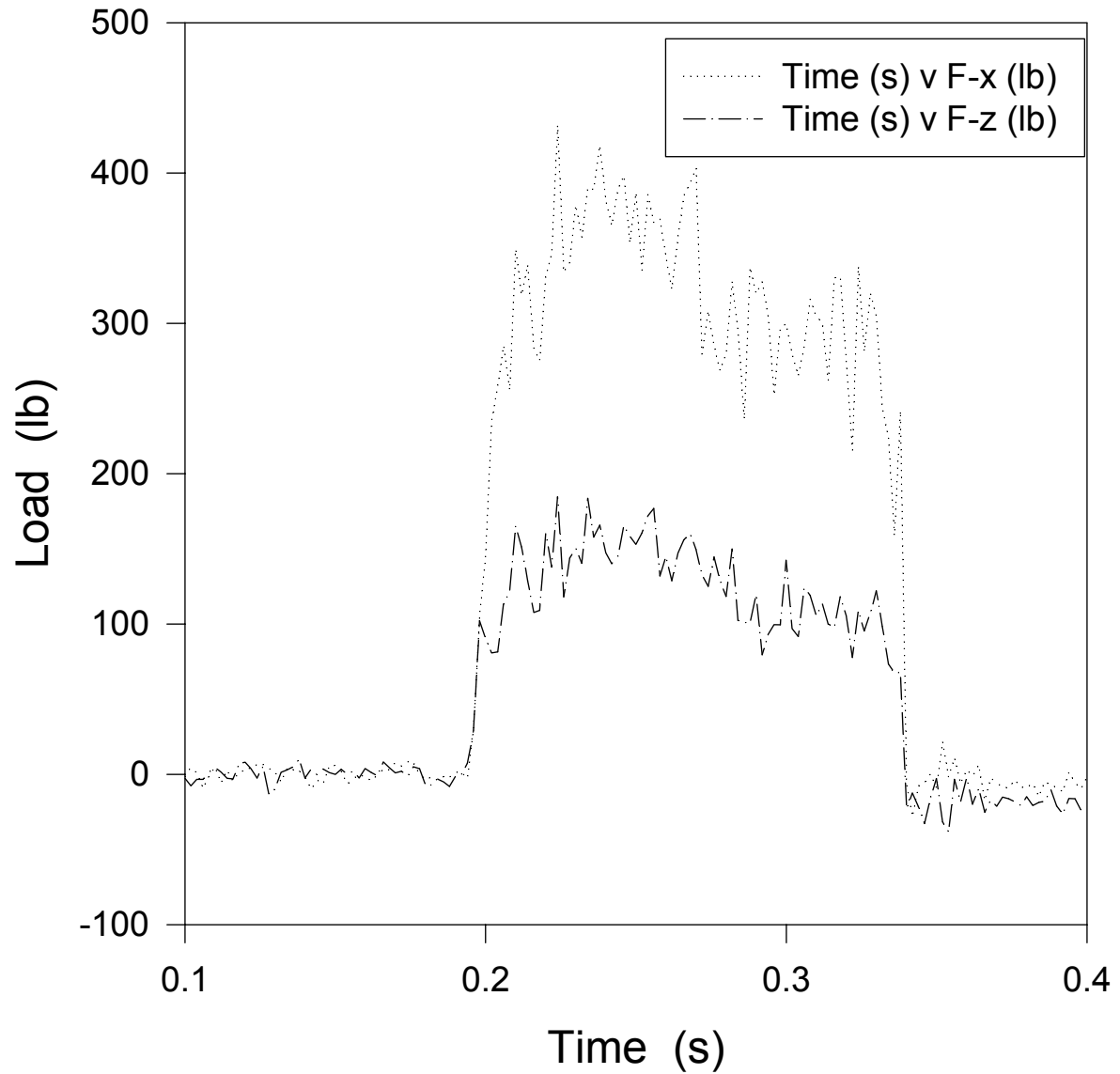


Figure A67: Sample DS-29 Load Trace

Test: Successful

Ice Type: Spray Ice

Test temperature: -20° C

Horizontal Force:  $123 \pm 31$  lbs

Vertical Force:  $309 \pm 71$  lbs

## DS-30

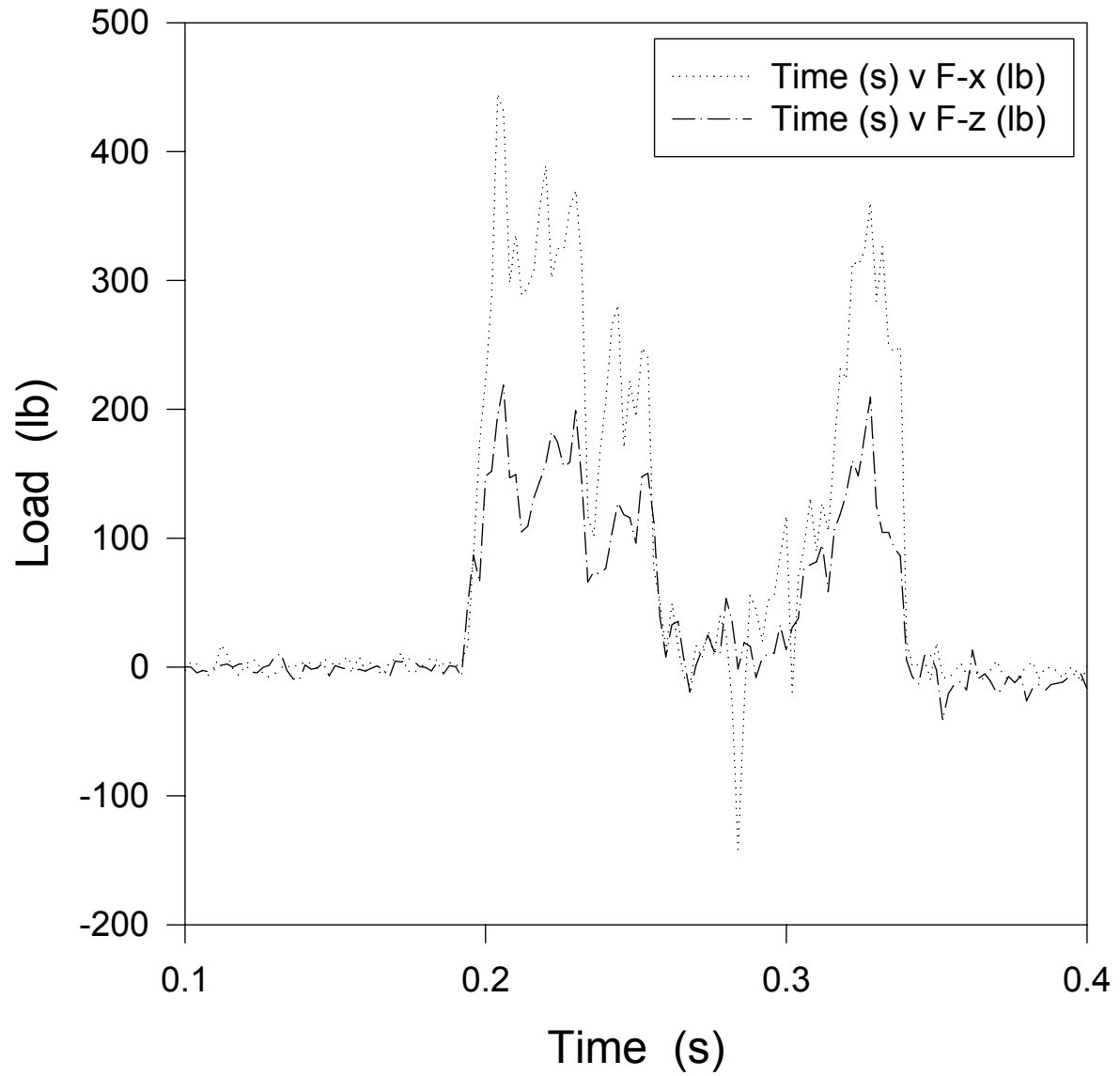


Figure A68: Sample DS-30 Load Trace

Test: Successful

Ice Type: Spray Ice

Test temperature: -20° C

Horizontal Force:  $89 \pm 62$  lbs

Vertical Force:  $172 \pm 137$  lbs

## **APPENDIX B**

### Individual Test Results for Chemical Testing

Note: for each test, the following information is provided:

Did the test give a zero or non-zero load response (non-zero being statistically different from a zero load, both vertically and horizontally)?

What type of chemical was used?

How long after application was the scrape test conducted?

What was the average and standard deviation for the horizontal force?

What was the average and standard deviation for the vertical force?

Note that in all the Chemical tests, the temperature was  $-5^{\circ}\text{C}$  and the ice type was refrozen ice.

## C410-1

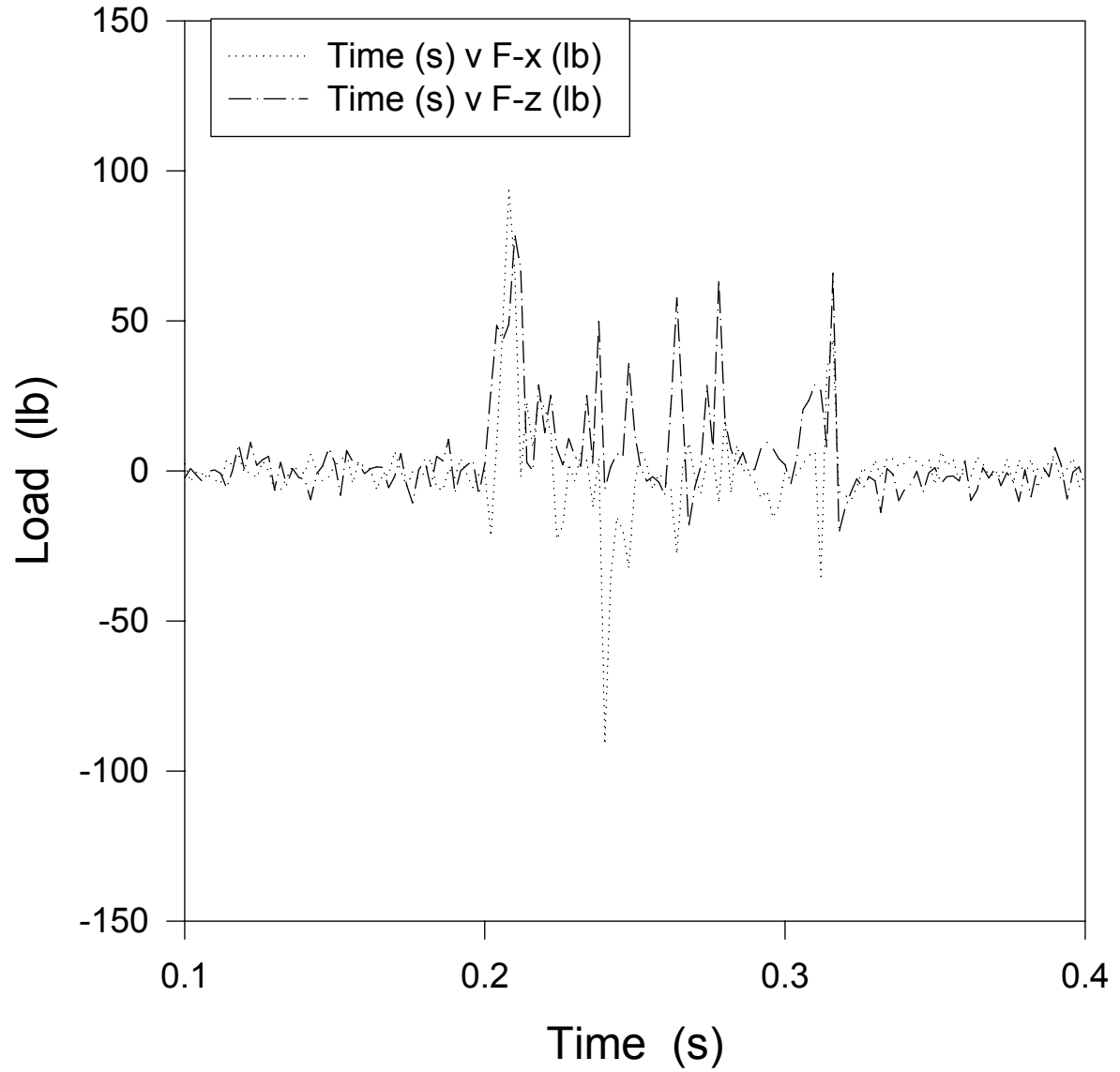


Figure B1: Sample C410-1 Load Trace  
Test: Zero Load Result  
Chemical Type: Solid Calcium Chloride  
Delay Time: Ten Minutes  
Horizontal Force:  $11 \pm 21$  lbs  
Vertical Force:  $0.25 \pm 22$  lbs

## C410-2

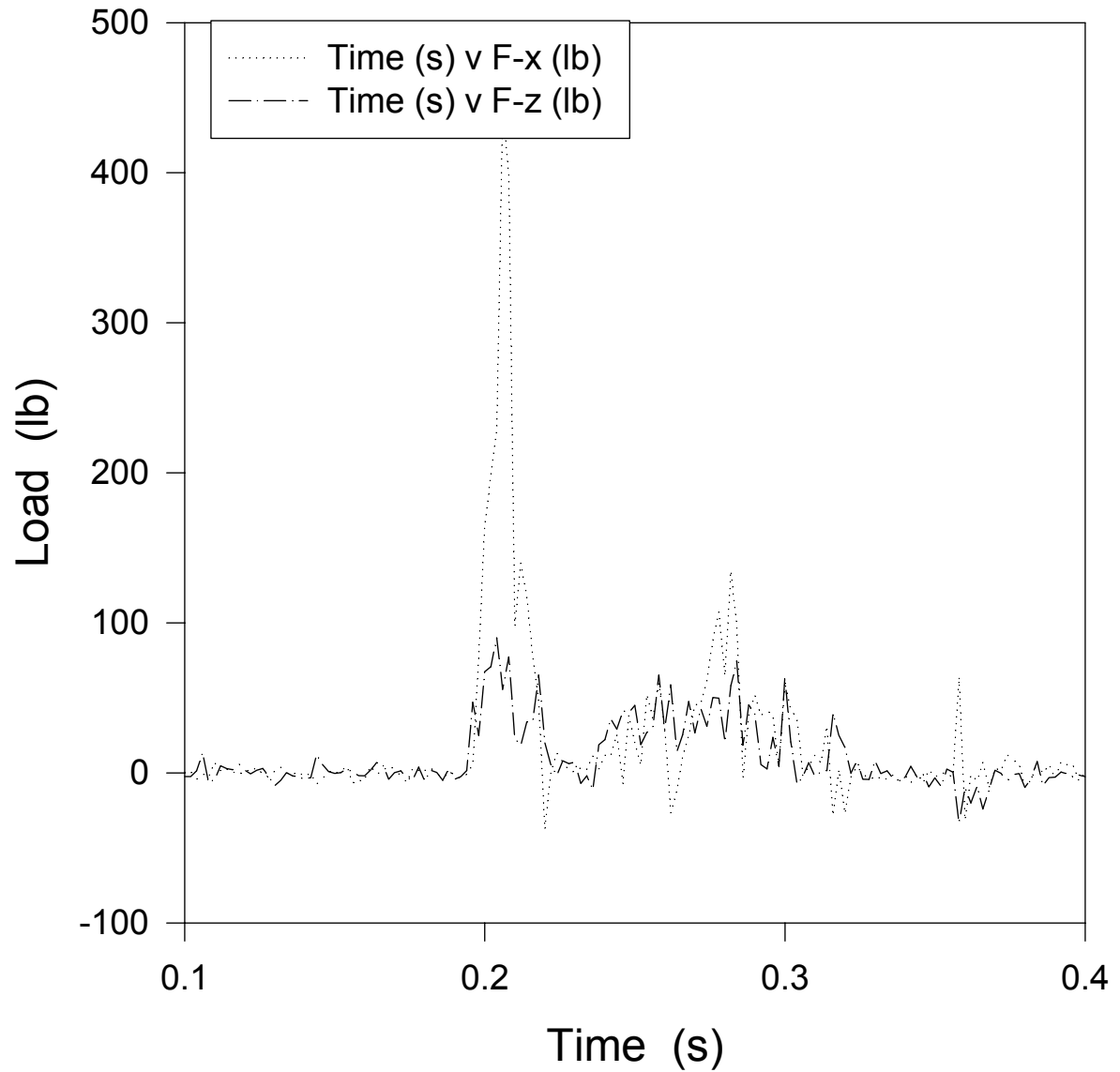


Figure B2: Sample C410-2 Load Trace  
Test: Zero Load Result  
Chemical Type: Solid Calcium Chloride  
Delay Time: Ten Minutes  
Horizontal Force:  $26 \pm 24$  lbs  
Vertical Force:  $46 \pm 82$  lbs

## C410-3

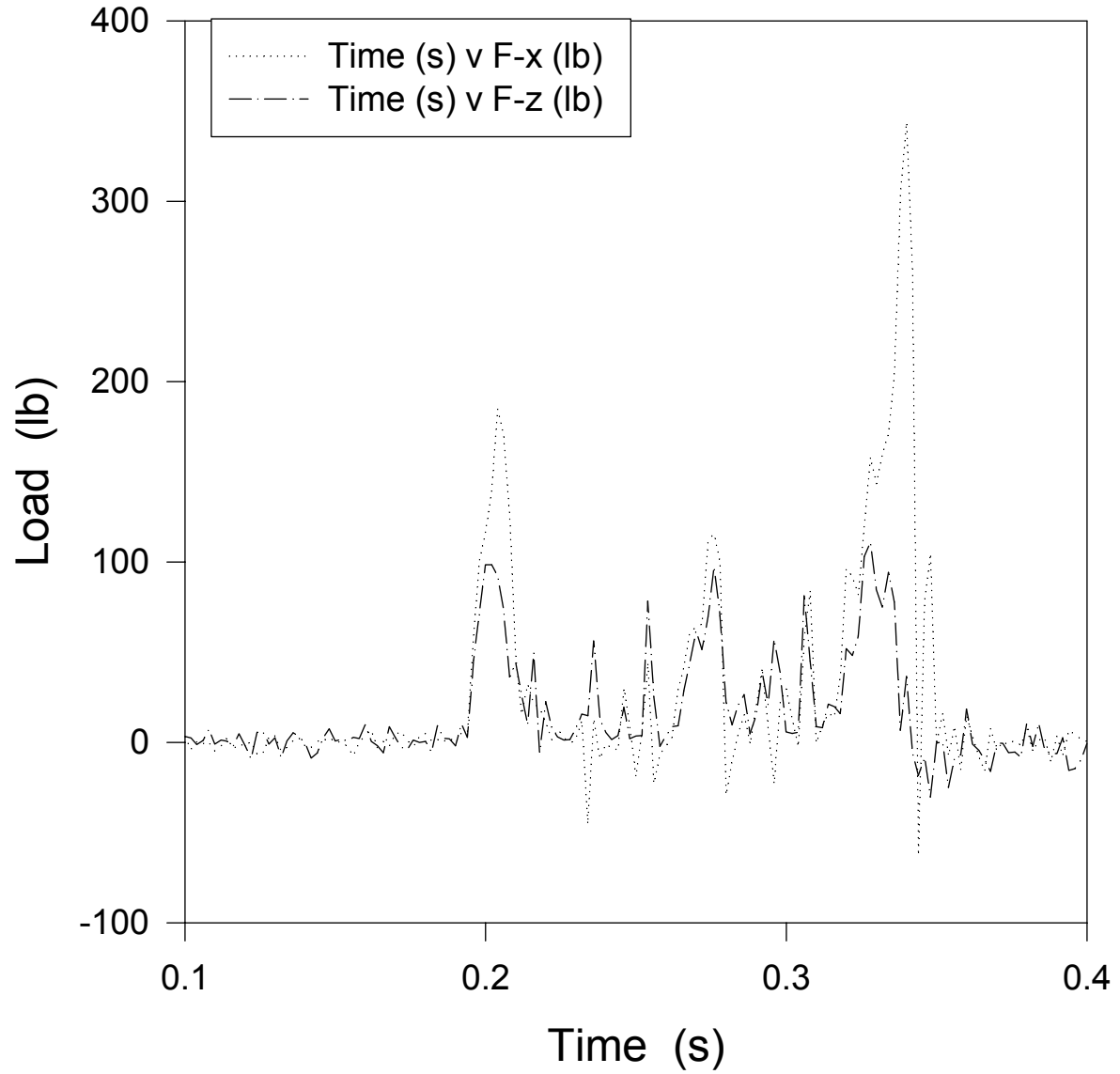


Figure B3: Sample C410-3 Load Trace  
Test: Zero Load Result  
Chemical Type: Solid Calcium Chloride  
Delay Time: Ten Minutes  
Horizontal Force:  $35 \pm 32$  lbs  
Vertical Force:  $51 \pm 74$  lbs

## C420-1

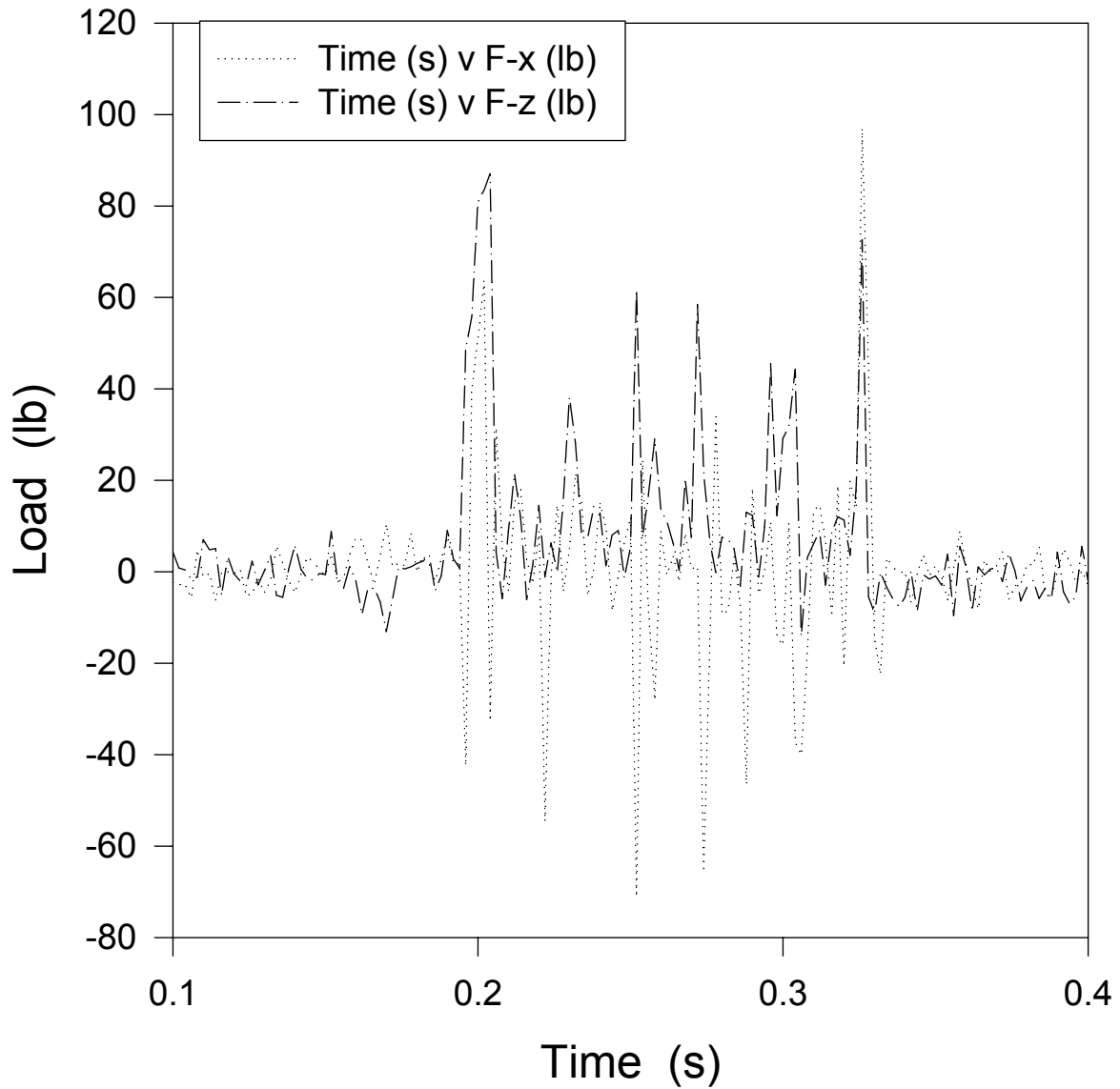


Figure B4: Sample C420-1 Load Trace  
Test: Zero Load Result  
Chemical Type: Solid Calcium Chloride  
Delay Time: Twenty Minutes  
Horizontal Force:  $17 \pm 22$  lbs  
Vertical Force:  $1.1 \pm 26$  lbs

## C420-2

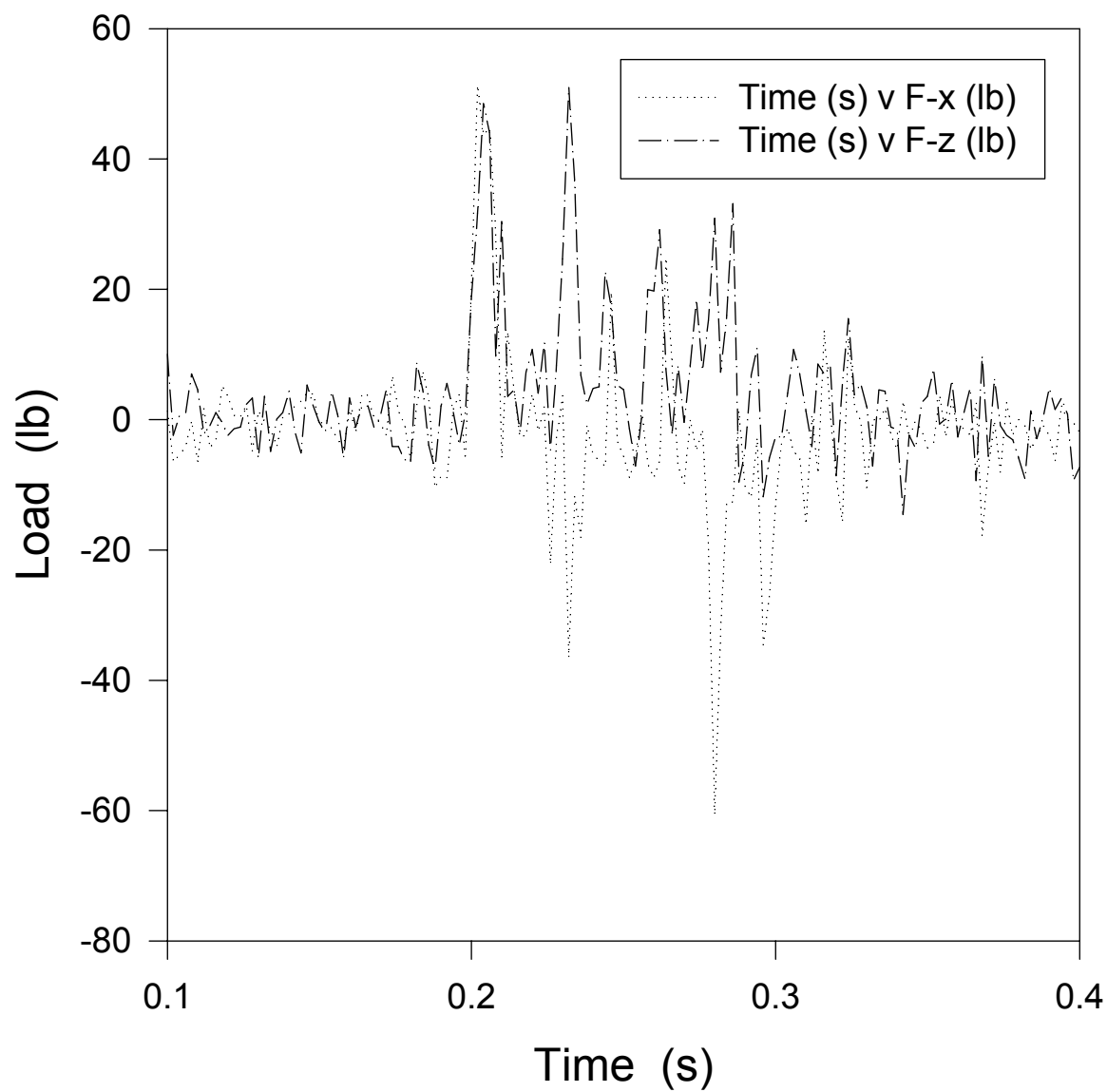


Figure B5: Sample C420-2 Load Trace  
Test: Zero Load Result  
Chemical Type: Solid Calcium Chloride  
Delay Time: Twenty Minutes  
Horizontal Force:  $9.7 \pm 14$  lbs  
Vertical Force:  $-3.1 \pm 17$  lbs



## C420-3

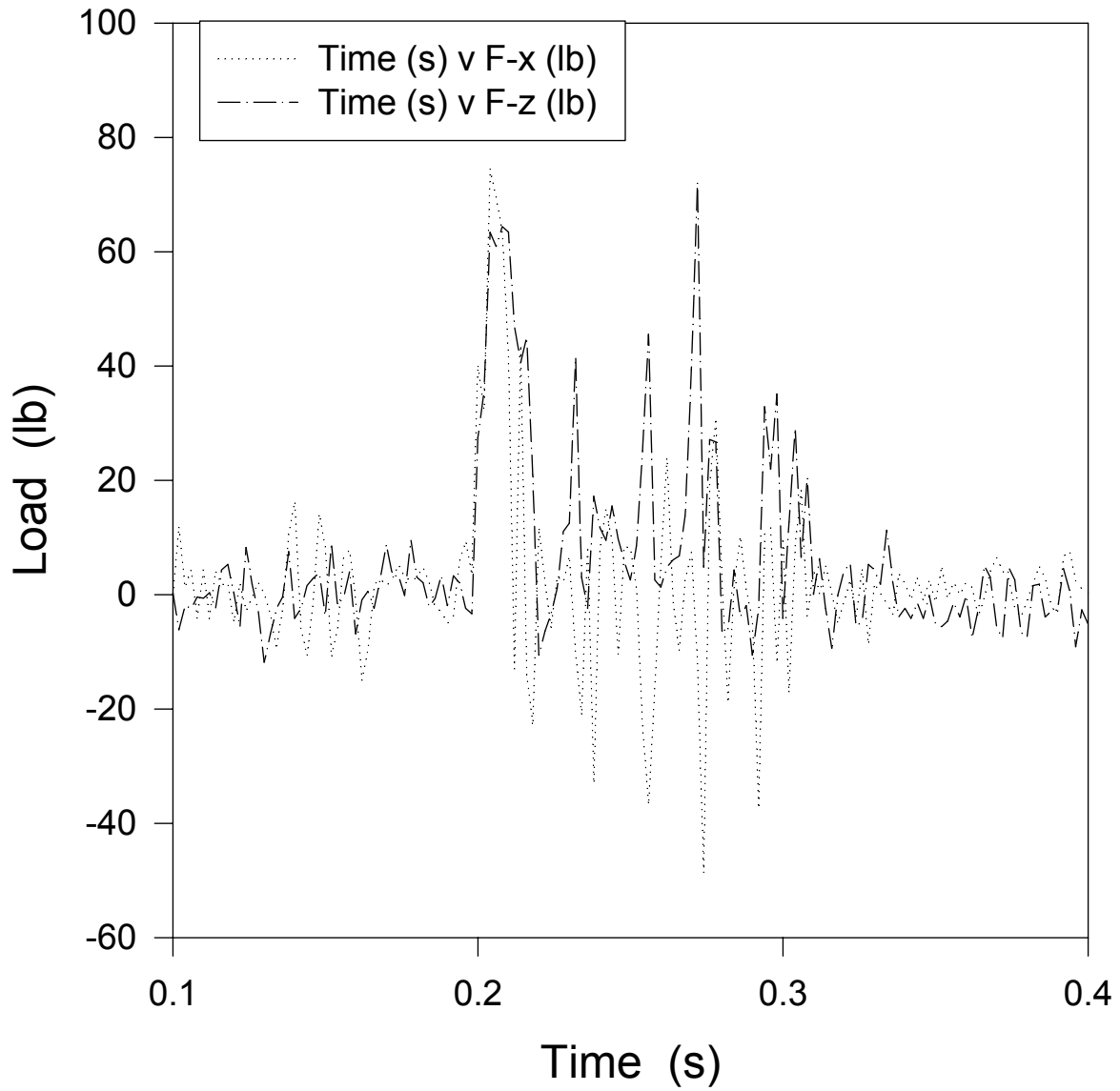


Figure B6: Sample C420-3 Load Trace  
Test: Zero Load Result  
Chemical Type: Solid Calcium Chloride  
Delay Time: Twenty Minutes  
Horizontal Force:  $15 \pm 21$  lbs  
Vertical Force:  $3.5 \pm 22$  lbs

## C430-1

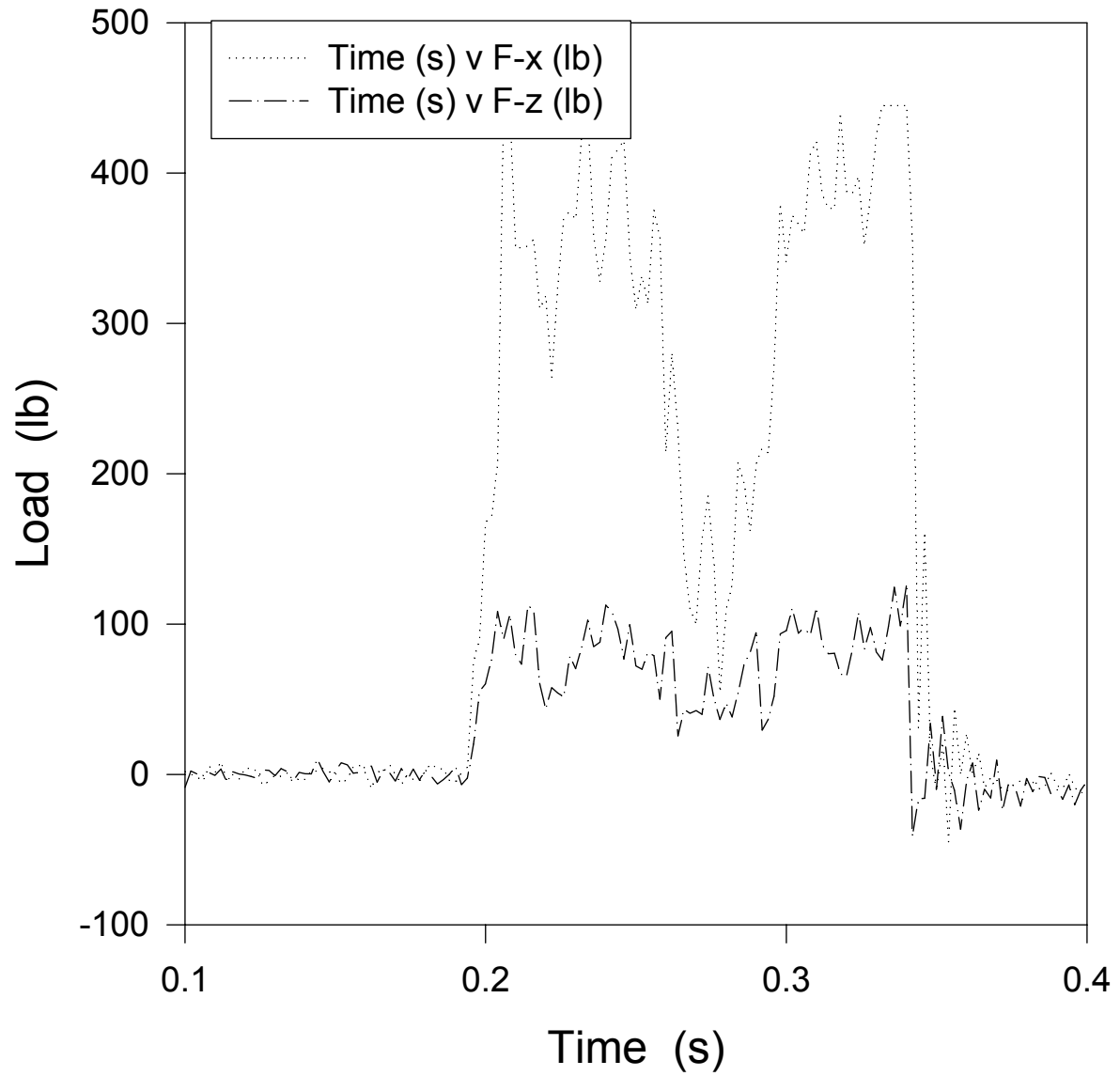


Figure B7: Sample C430-1 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Solid Calcium Chloride  
Delay Time: Thirty Minutes  
Horizontal Force:  $71 \pm 33$  lbs  
Vertical Force:  $294 \pm 127$  lbs

## C430-2

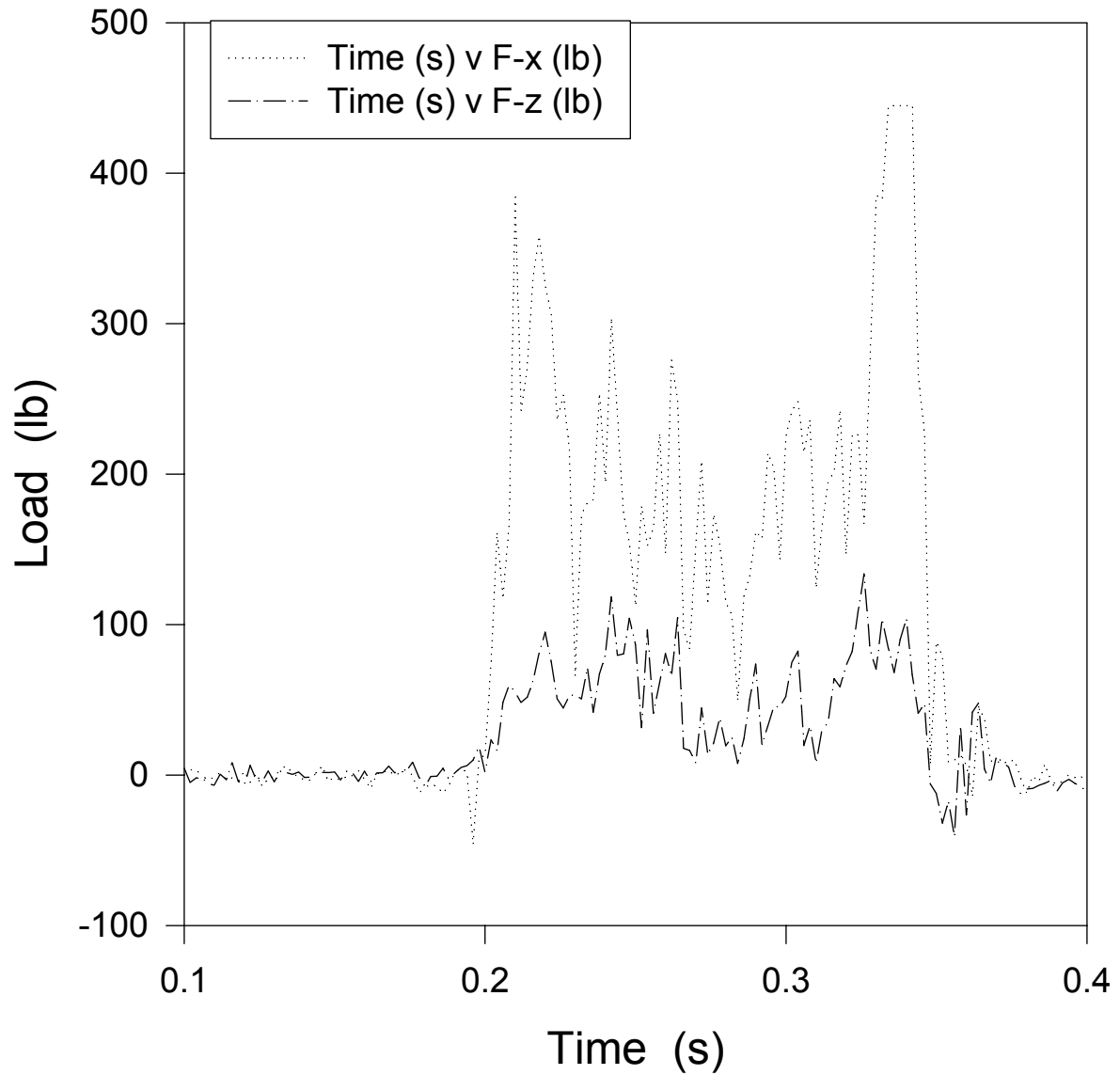


Figure B8: Sample C430-2 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Solid Calcium Chloride  
Delay Time: Thirty Minutes  
Horizontal Force:  $50 \pm 35$  lbs  
Vertical Force:  $192 \pm 112$  lbs

## C430-3

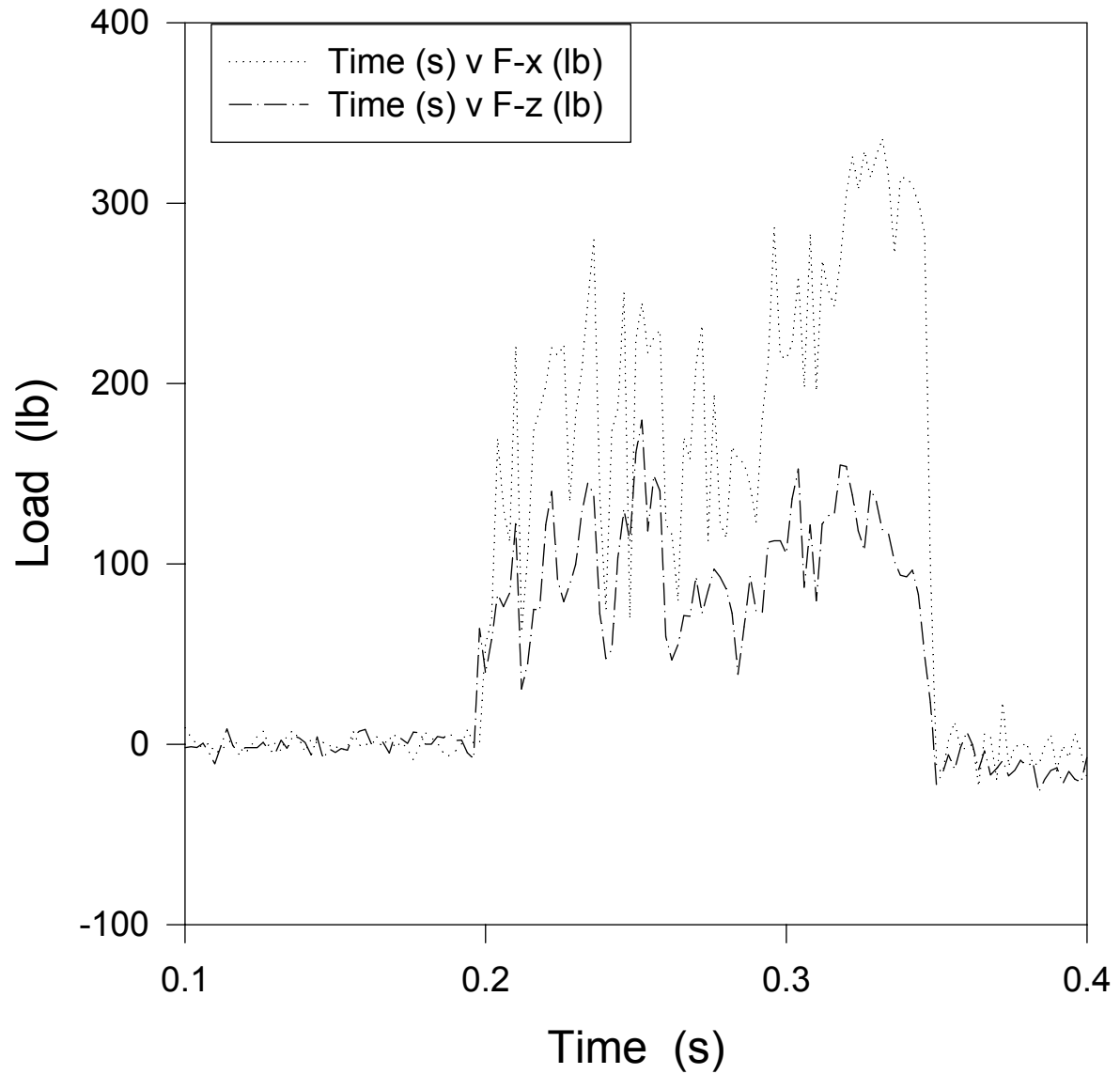


Figure B9: Sample C430-3 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Solid Calcium Chloride  
Delay Time: Thirty Minutes  
Horizontal Force:  $98 \pm 35$  lbs  
Vertical Force:  $202 \pm 79$  lbs

## B410-1

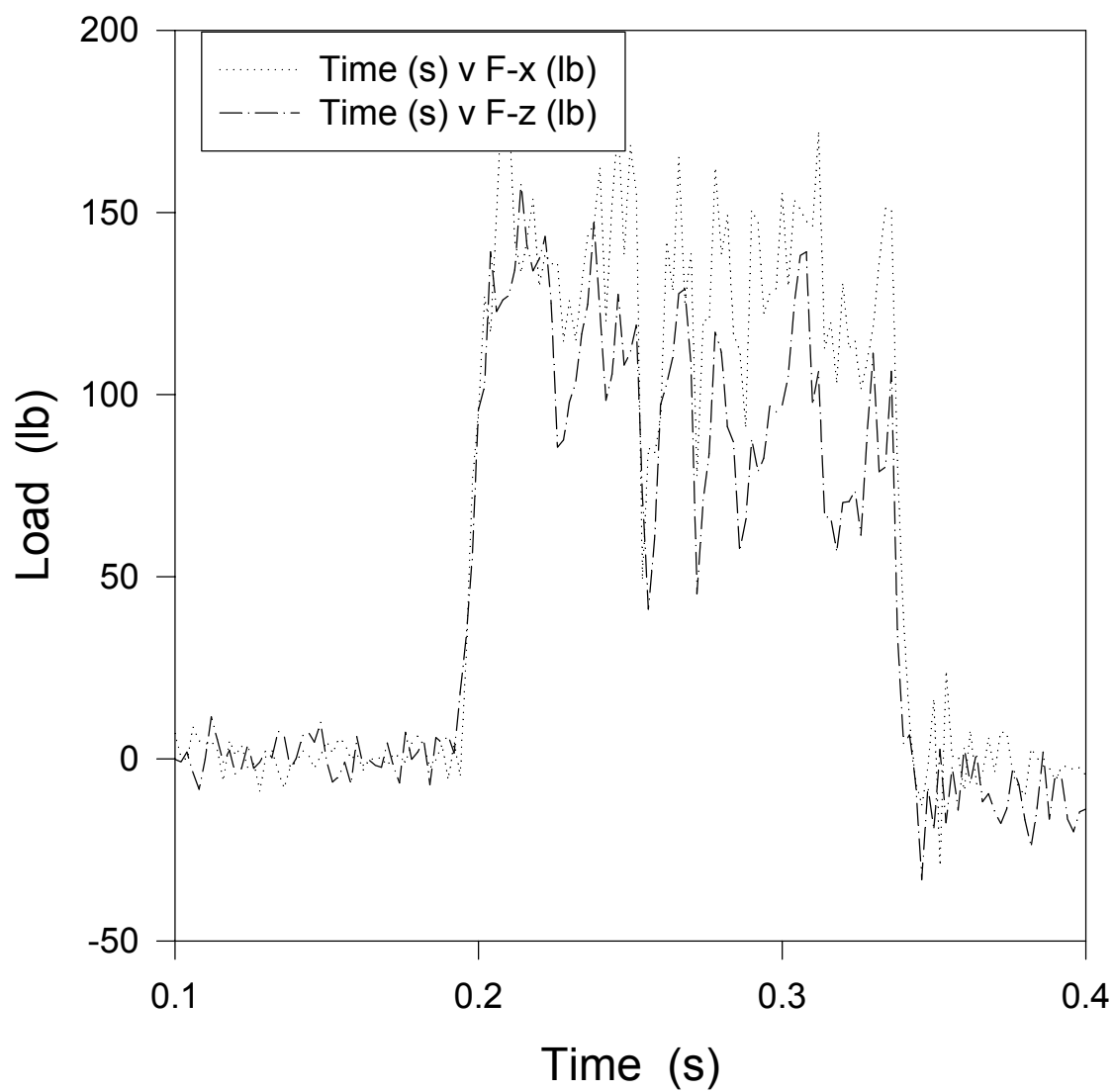


Figure B10: Sample B410-1 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Liquid Sodium Chloride Brine  
Delay Time: Ten Minutes  
Horizontal Force:  $95 \pm 34$  lbs  
Vertical Force:  $125 \pm 36$  lbs

## B410-2

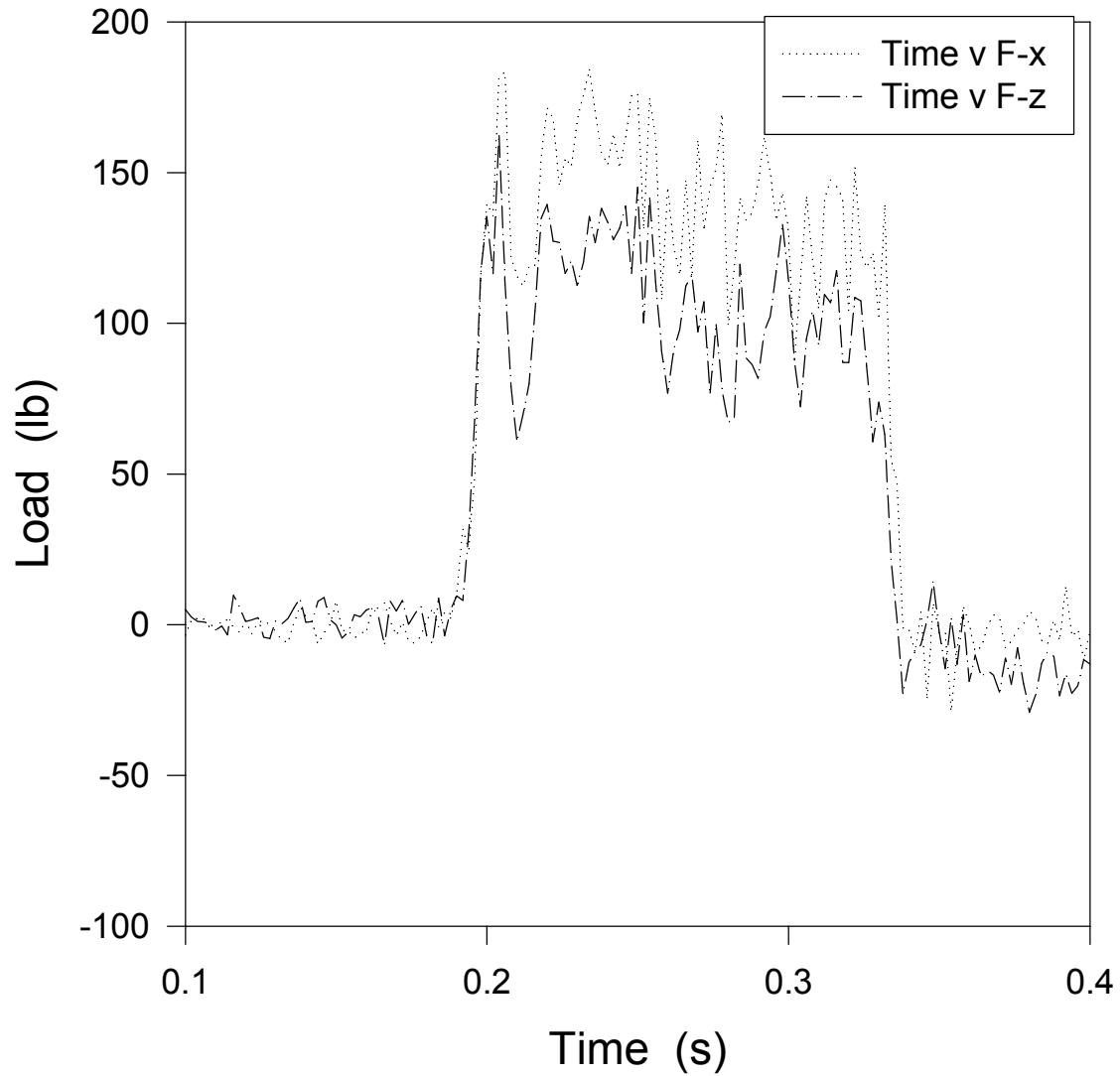


Figure B11: Sample B410-2 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Liquid Sodium Chloride Brine  
Delay Time: Ten Minutes  
Horizontal Force:  $98 \pm 34$  lbs  
Vertical Force:  $131 \pm 34$  lbs

## B410-3

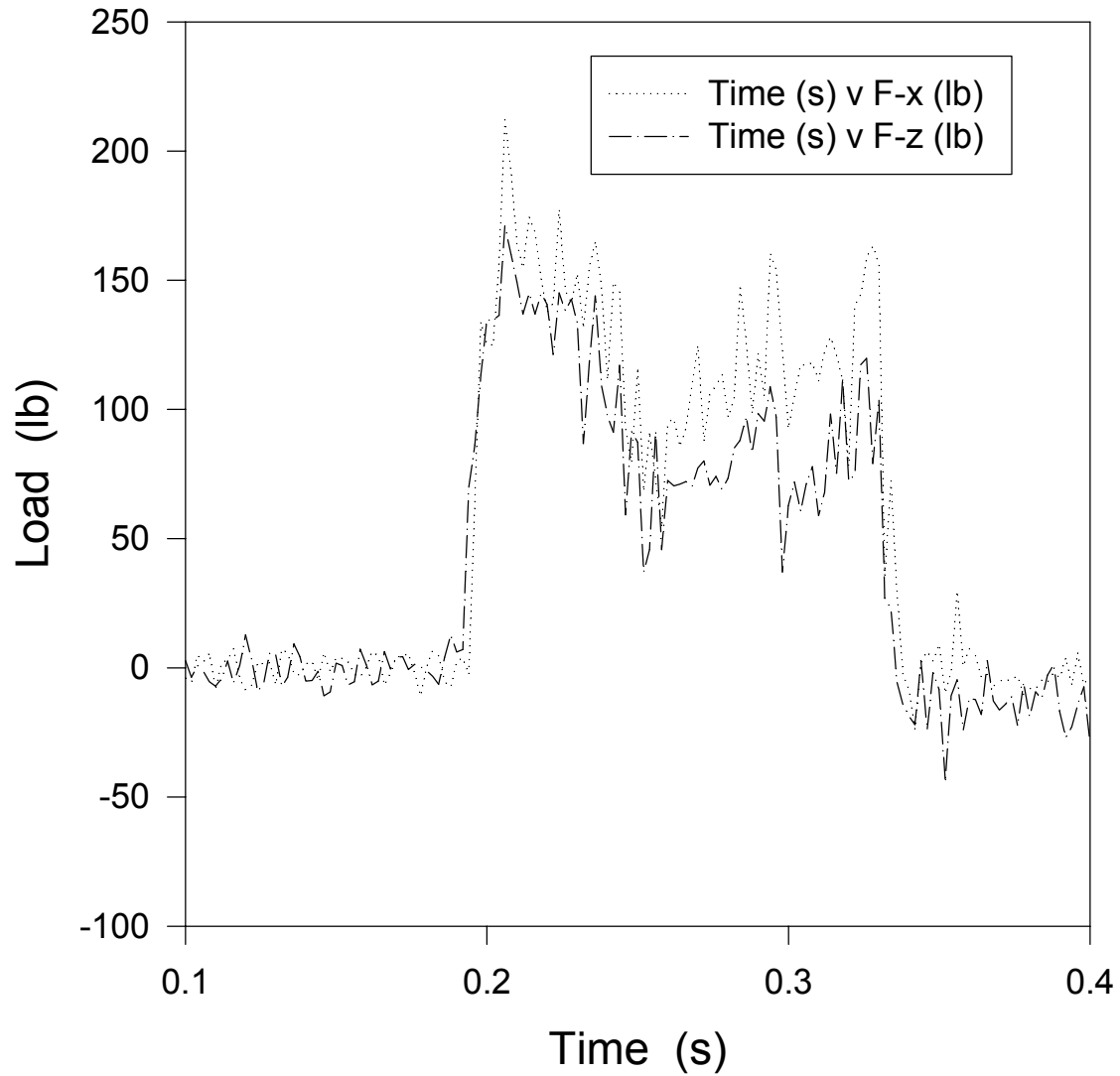


Figure B12: Sample B410-3 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Liquid Sodium Chloride Brine  
Delay Time: Ten Minutes  
Horizontal Force:  $95 \pm 34$  lbs  
Vertical Force:  $122 \pm 37$  lbs

## B420-1

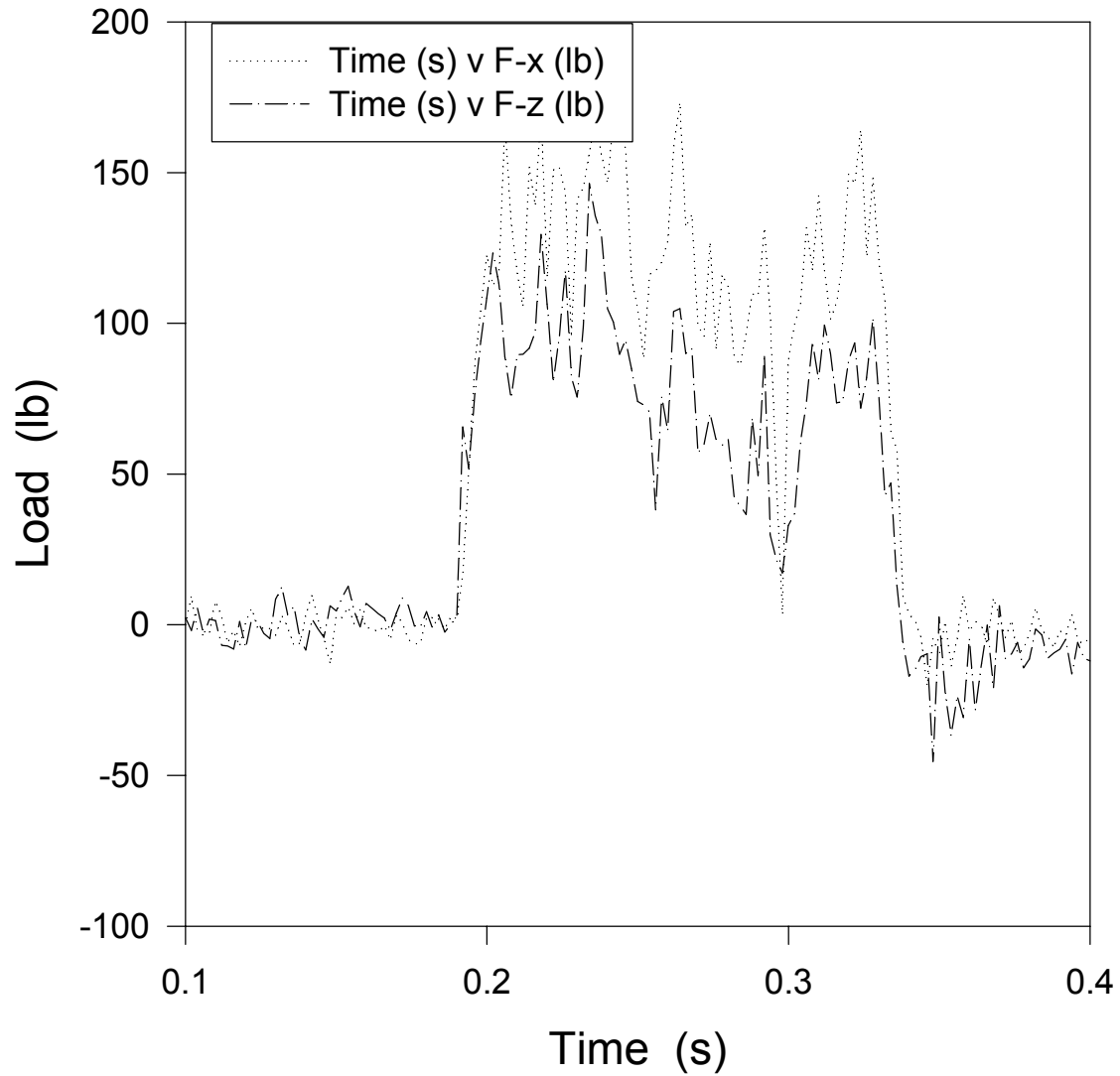


Figure B13: Sample B420-1 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Liquid Sodium Chloride Brine  
Delay Time: Twenty Minutes  
Horizontal Force:  $78 \pm 28$  lbs  
Vertical Force:  $119 \pm 34$  lbs



## B420-2

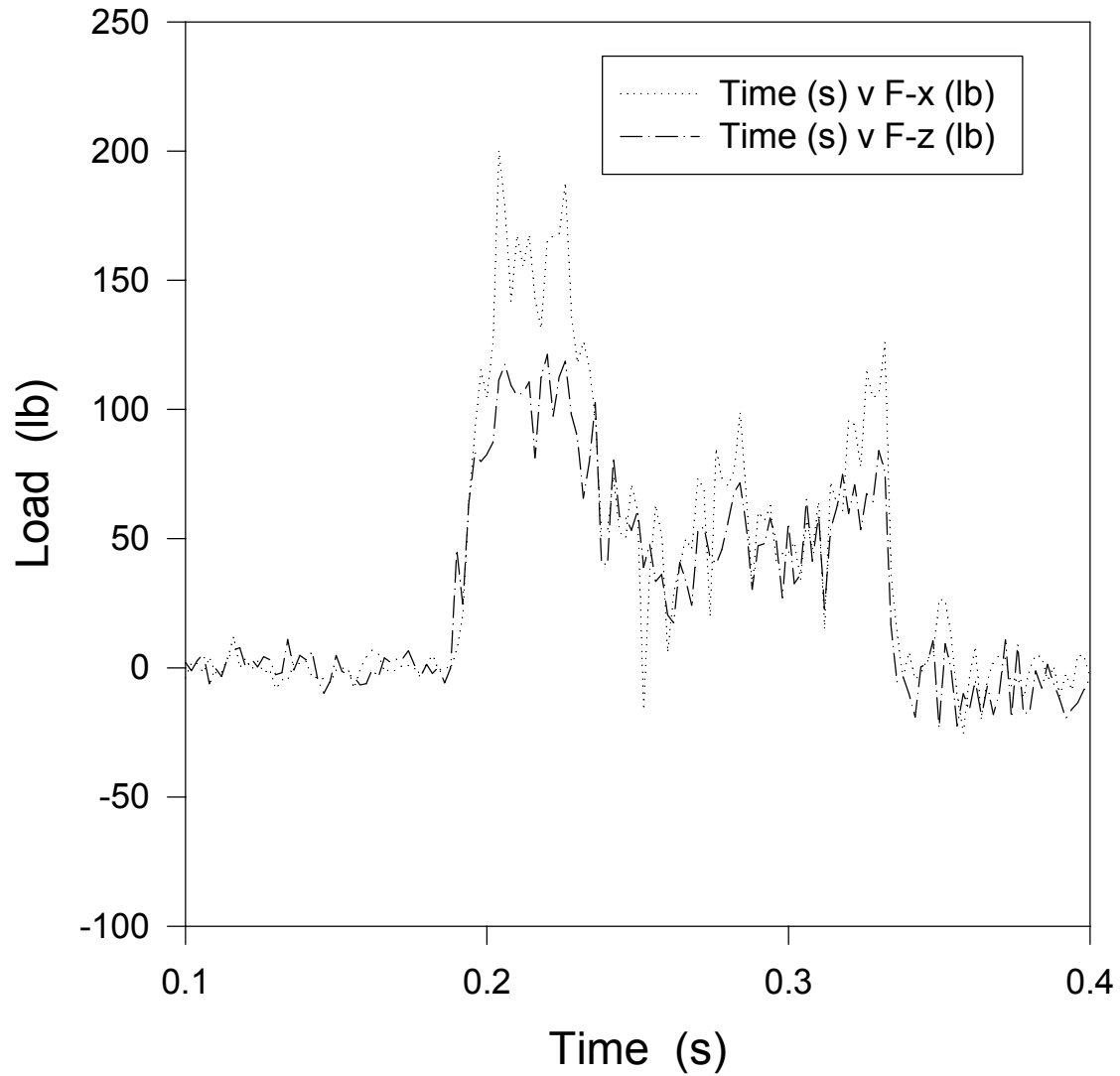


Figure B14: Sample B420-2 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Liquid Sodium Chloride Brine  
Delay Time: Twenty Minutes  
Horizontal Force:  $63 \pm 28$  lbs  
Vertical Force:  $82 \pm 48$  lbs

## B420-3

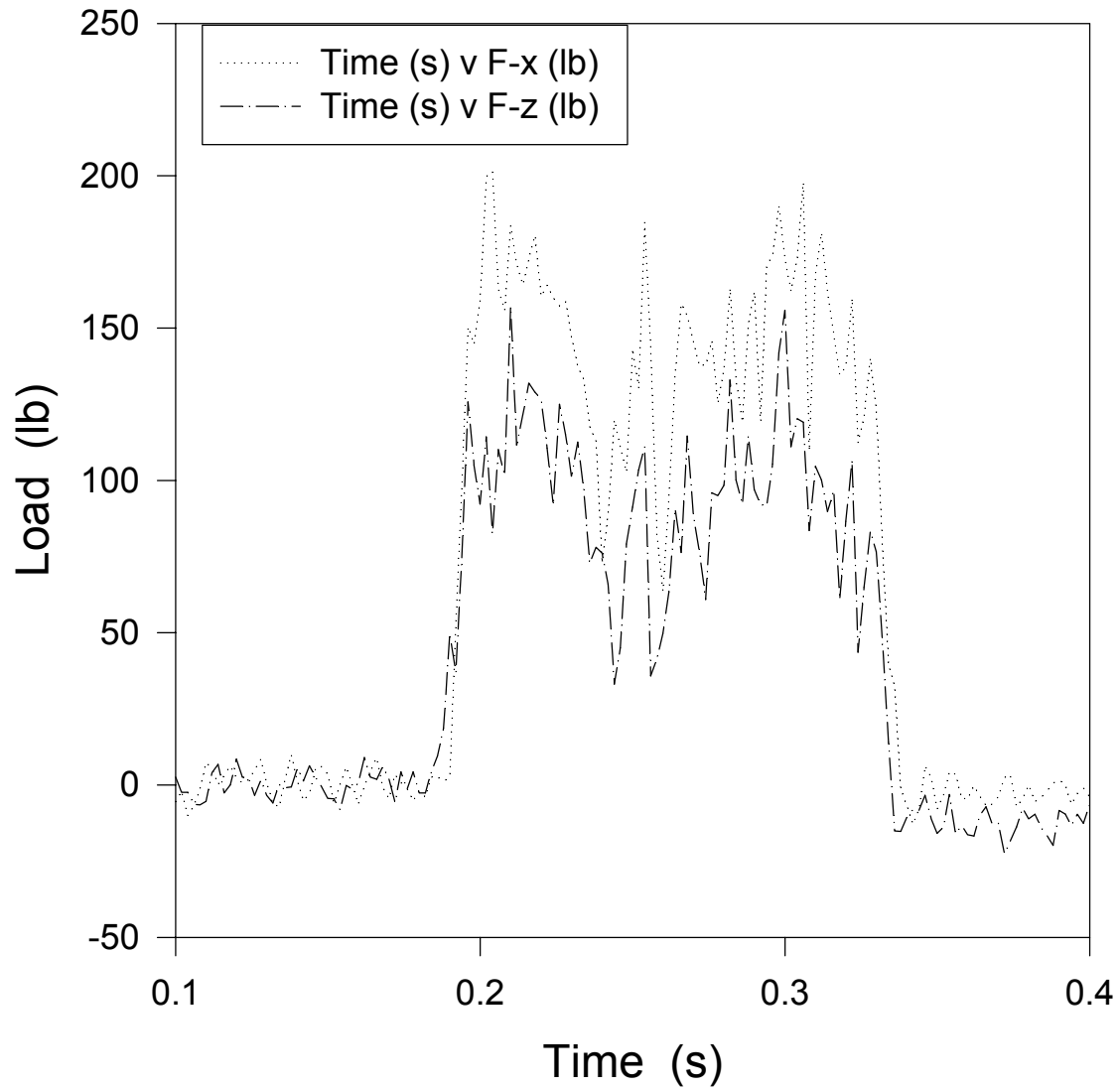


Figure B15: Sample B420-3 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Liquid Sodium Chloride Brine  
Delay Time: Twenty Minutes  
Horizontal Force:  $91 \pm 30$  lbs  
Vertical Force:  $147 \pm 31$  lbs

## B430-1

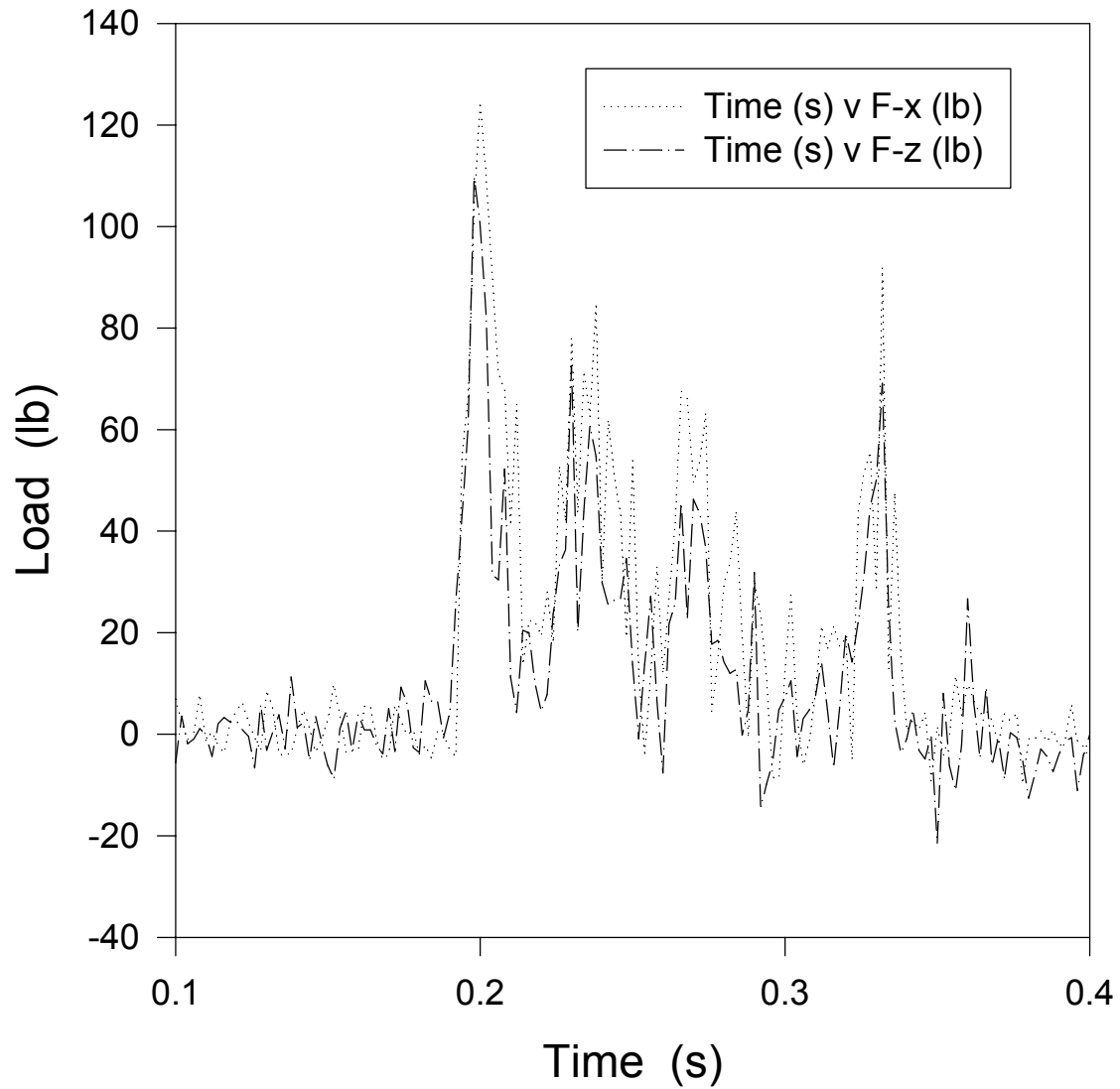


Figure B16: Sample B430-1 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Liquid Sodium Chloride Brine  
Delay Time: Thirty Minutes  
Horizontal Force:  $25 \pm 24$  lbs  
Vertical Force:  $37 \pm 30$  lbs

## B430-2

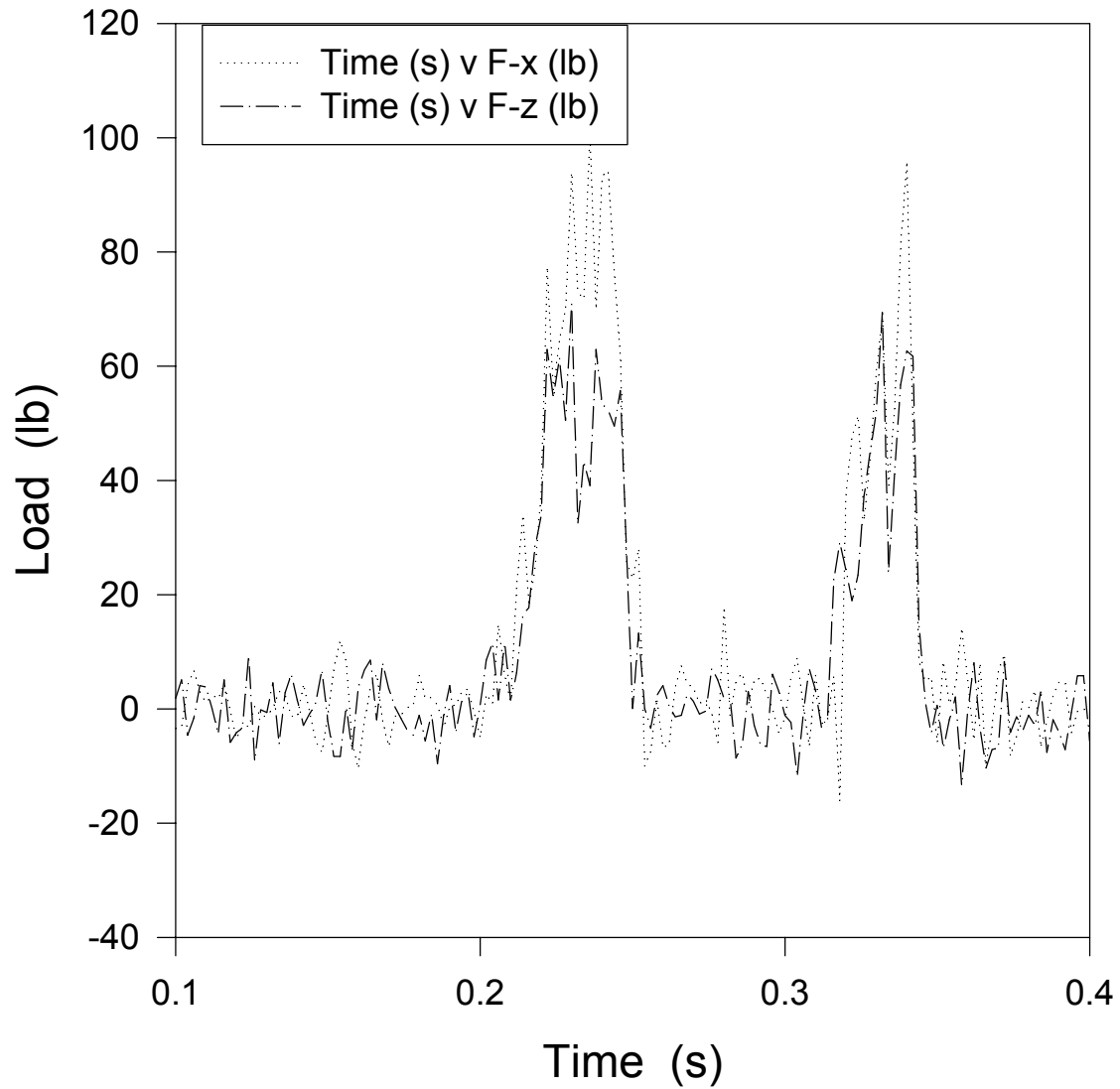


Figure B17: Sample B430-2 Load Trace

Test: Zero Load Result

Chemical Type: Liquid Sodium Chloride Brine

Delay Time: Thirty Minutes

Horizontal Force:  $20 \pm 24$  lbs

Vertical Force:  $27 \pm 33$  lbs

## B430-3

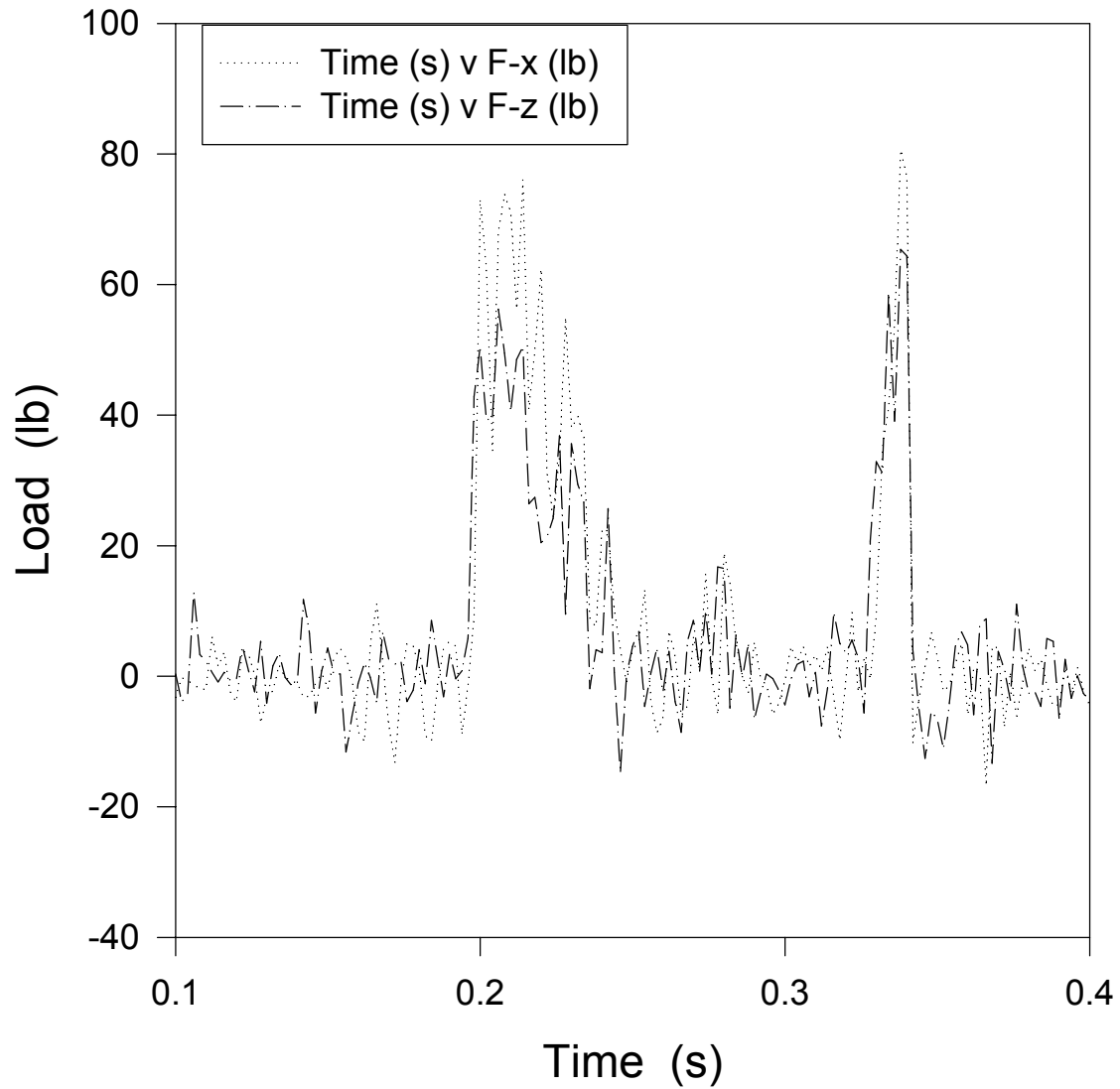


Figure B18: Sample B430-3 Load Trace  
Test: Zero Load Result  
Chemical Type: Liquid Sodium Chloride Brine  
Delay Time: Thirty Minutes  
Horizontal Force:  $15 \pm 20$  lbs  
Vertical Force:  $19 \pm 26$  lbs

## B440-1

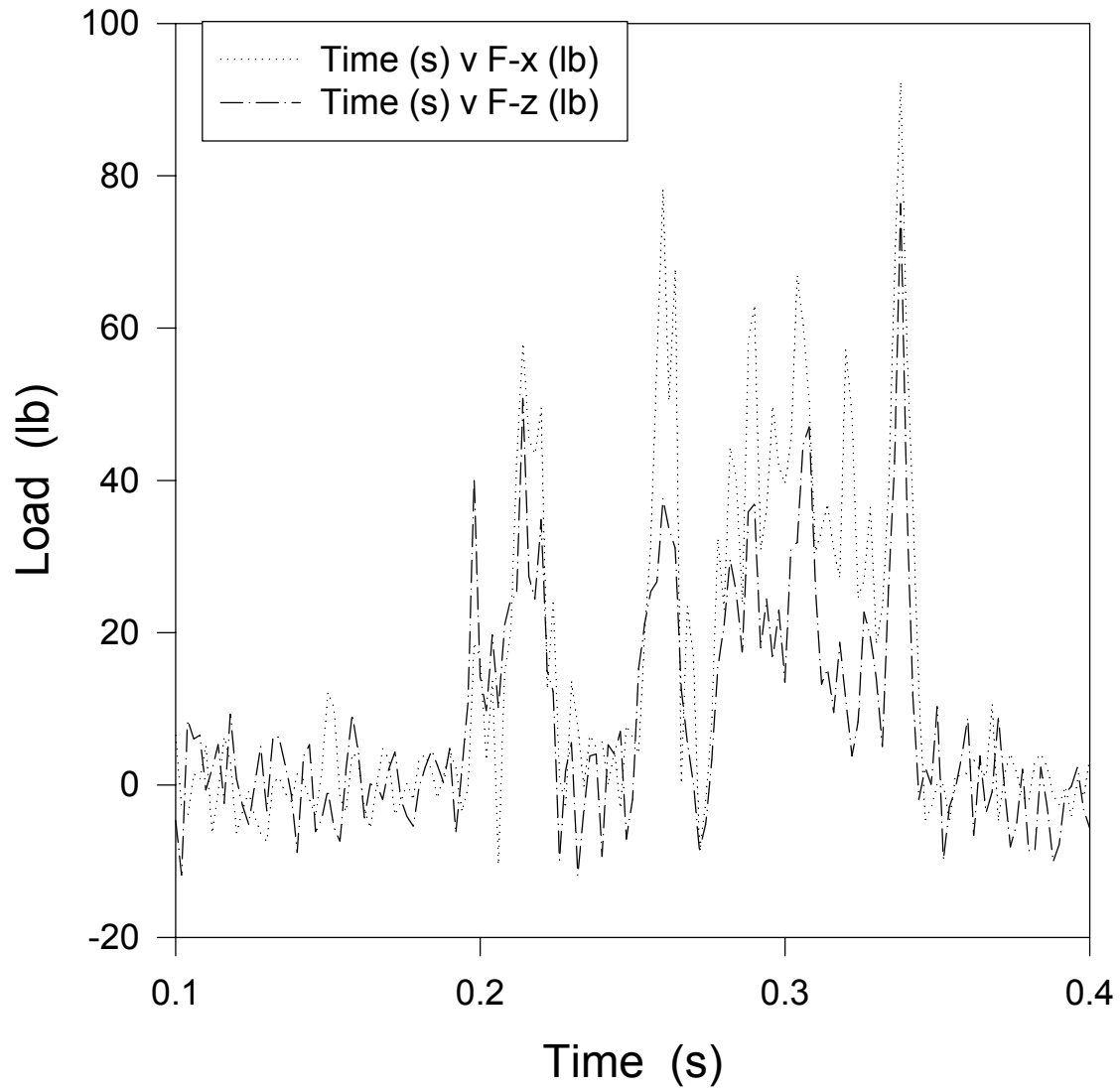


Figure B19: Sample B440-1 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Liquid Sodium Chloride Brine  
Delay Time: Forty Minutes  
Horizontal Force:  $18 \pm 16$  lbs  
Vertical Force:  $29 \pm 23$  lbs

## B440-2

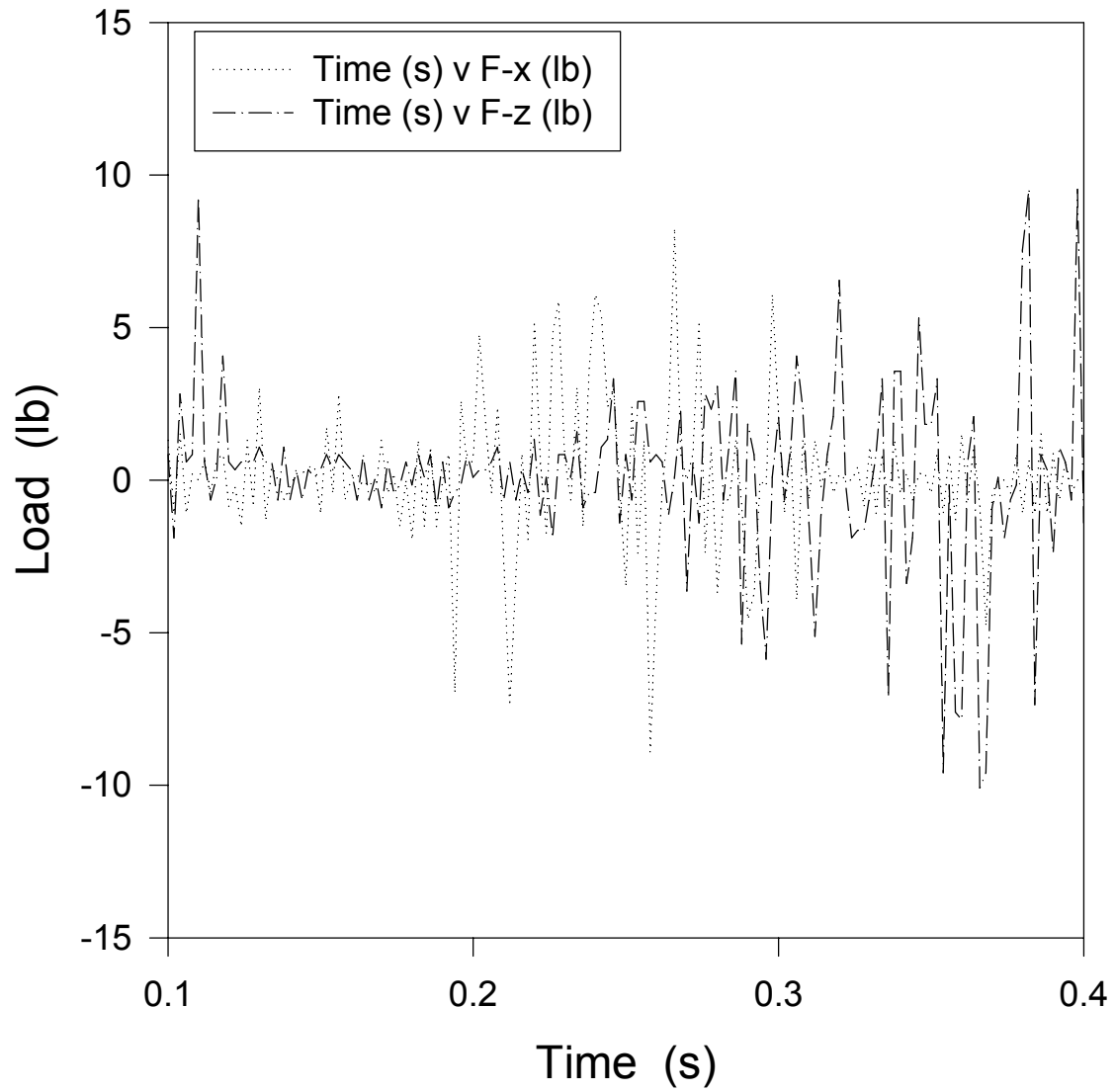


Figure B20: Sample B440-2 Load Trace  
Test: Zero Load Result  
Chemical Type: Liquid Sodium Chloride Brine  
Delay Time: Forty Minutes  
Horizontal Force:  $0 \pm 2$  lbs  
Vertical Force:  $0 \pm 3$  lbs

## B440-3

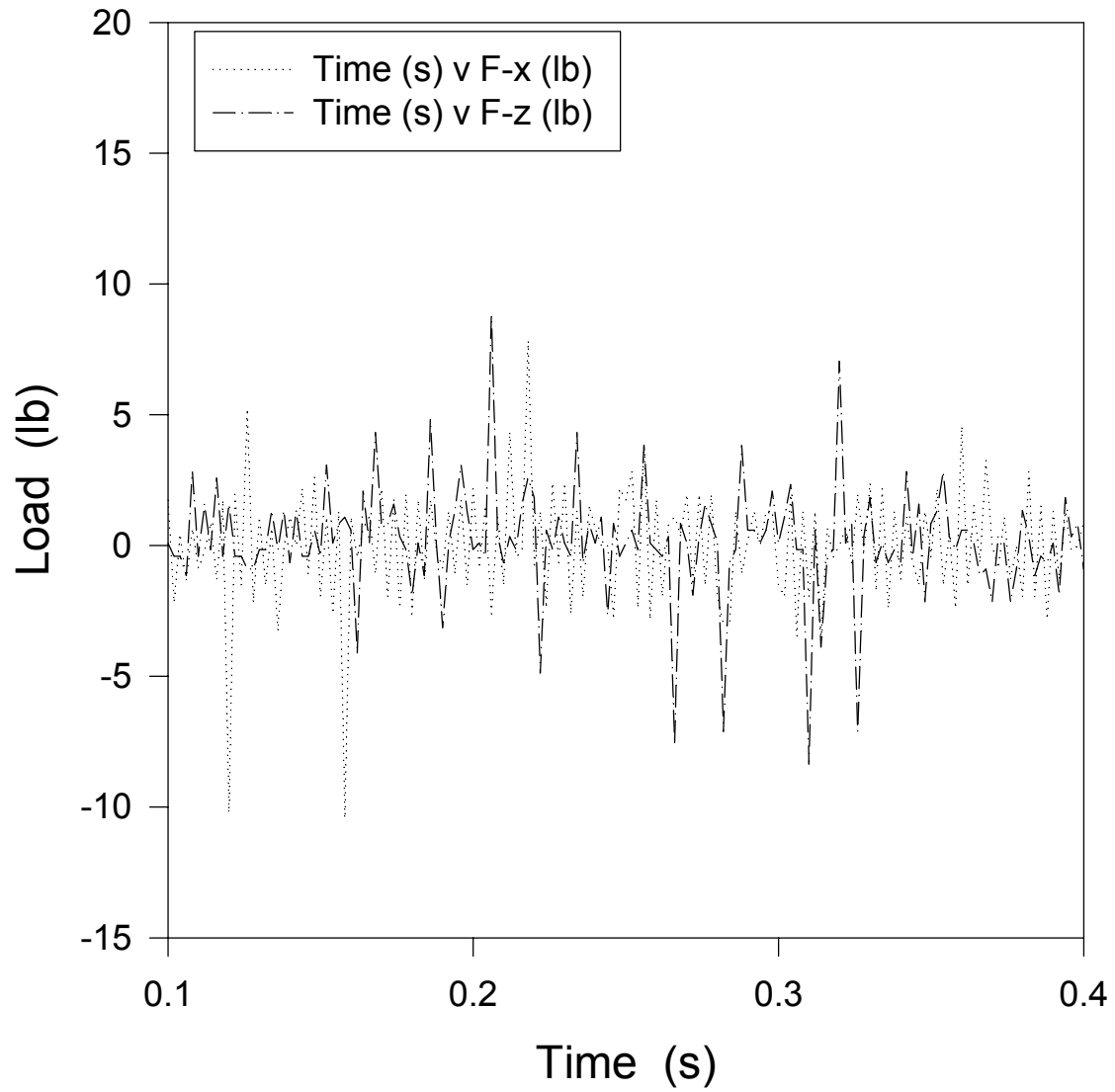


Figure B21: Sample B440-3 Load Trace  
Test: Zero Load Result  
Chemical Type: Liquid Sodium Chloride Brine  
Delay Time: Forty Minutes  
Horizontal Force:  $0 \pm 3$  lbs  
Vertical Force:  $0 \pm 2$  lbs



## S410-1

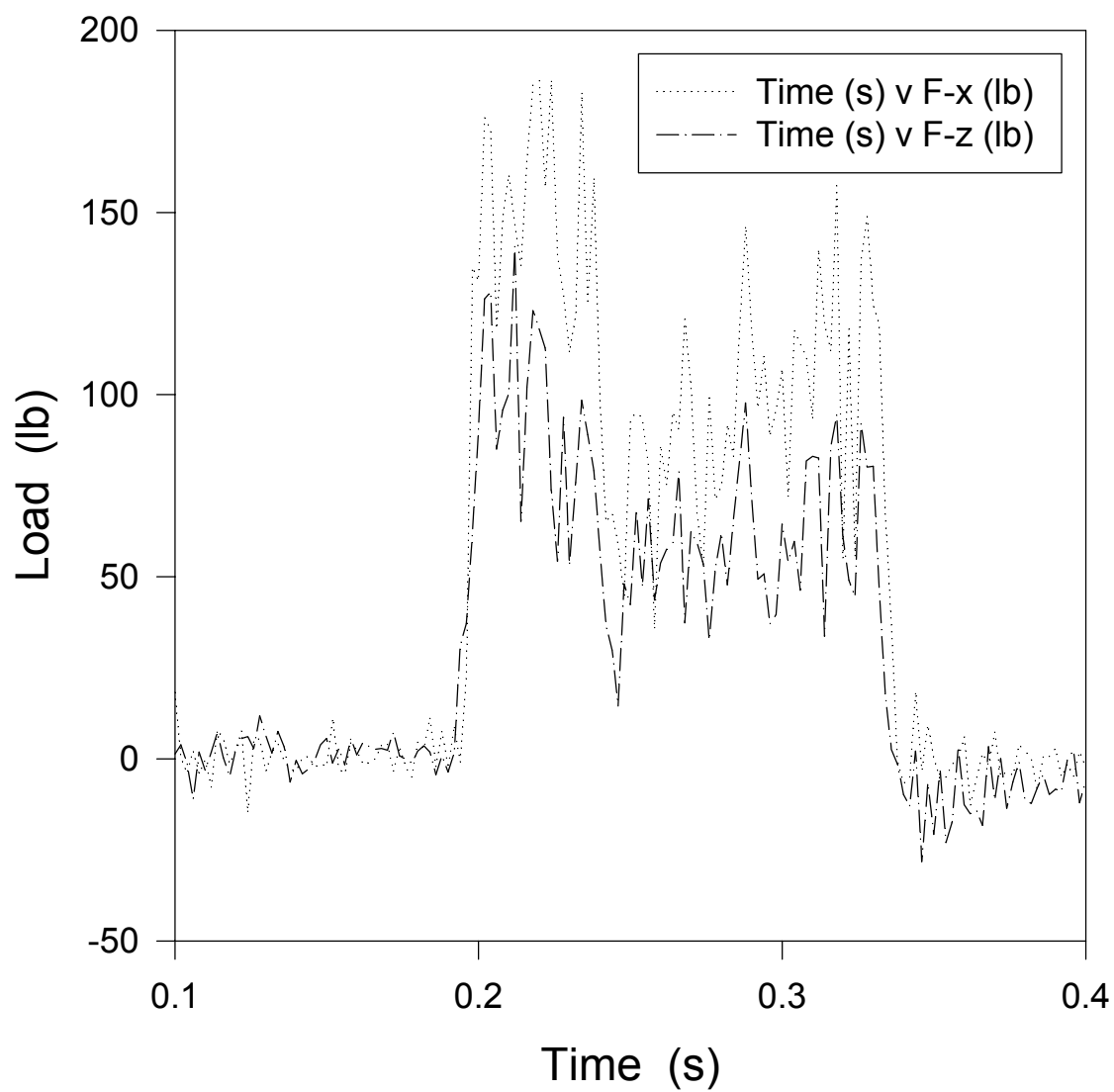


Figure B22: Sample S410-1 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Solid Sodium Chloride  
Delay Time: Ten Minutes  
Horizontal Force:  $68 \pm 27$  lbs  
Vertical Force:  $110 \pm 40$  lbs

## S410-2

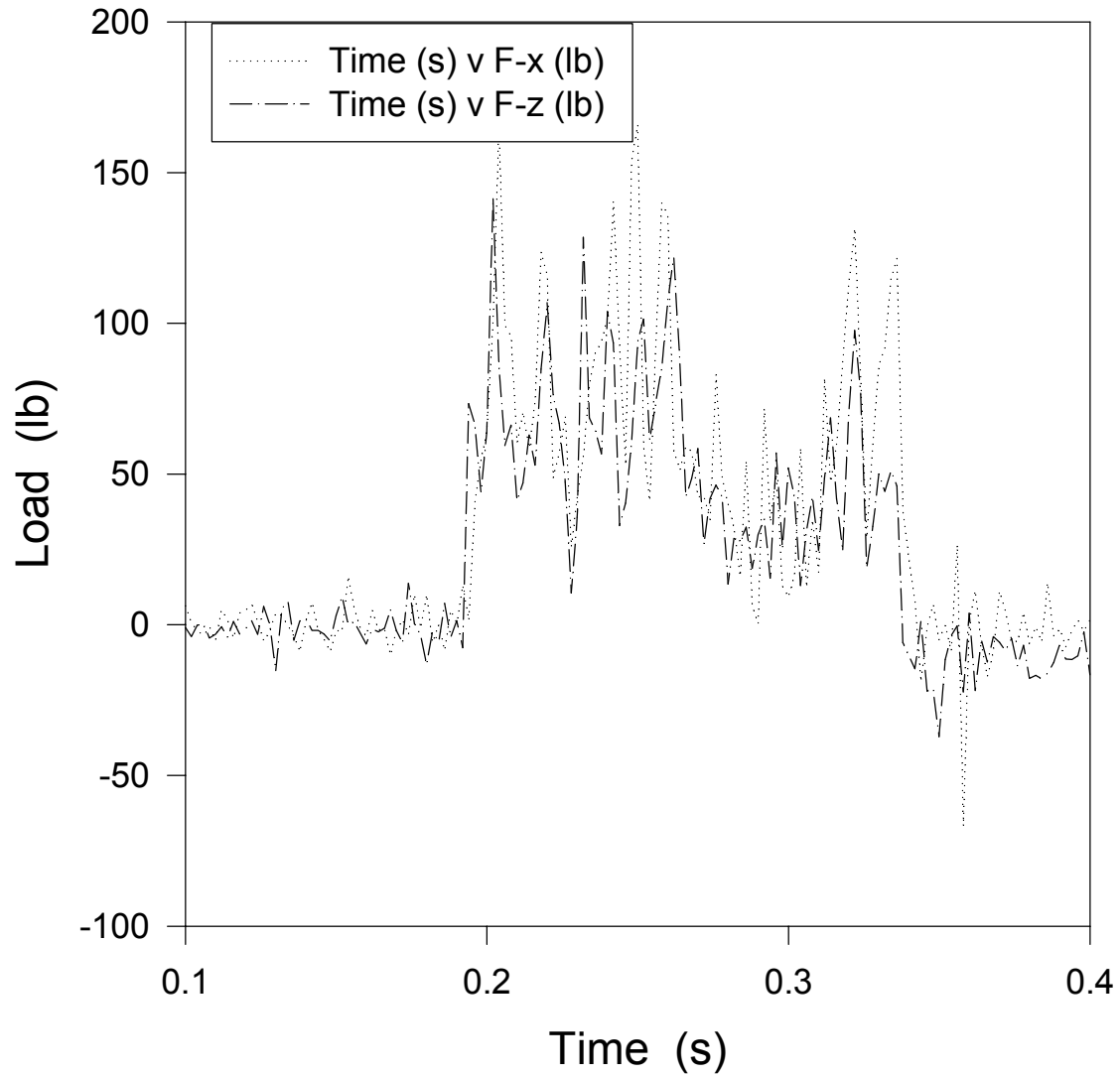


Figure B23: Sample S410-2 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Solid Sodium Chloride  
Delay Time: Ten Minutes  
Horizontal Force:  $57 \pm 29$  lbs  
Vertical Force:  $68 \pm 40$  lbs

## S410-3

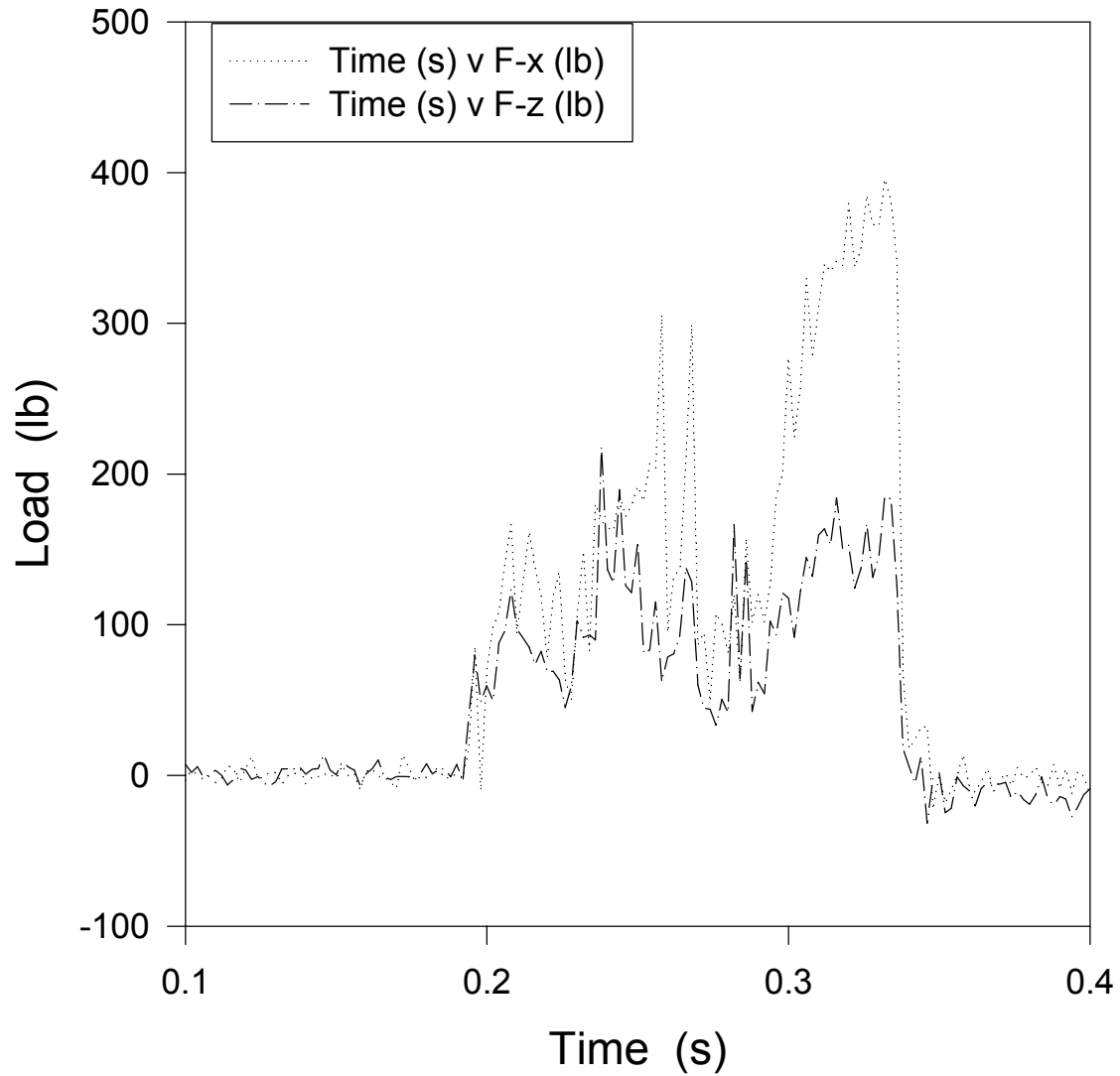


Figure B24: Sample S410-3 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Solid Sodium Chloride  
Delay Time: Ten Minutes  
Horizontal Force:  $103 \pm 45$  lbs  
Vertical Force:  $183 \pm 106$  lbs

## S420-1

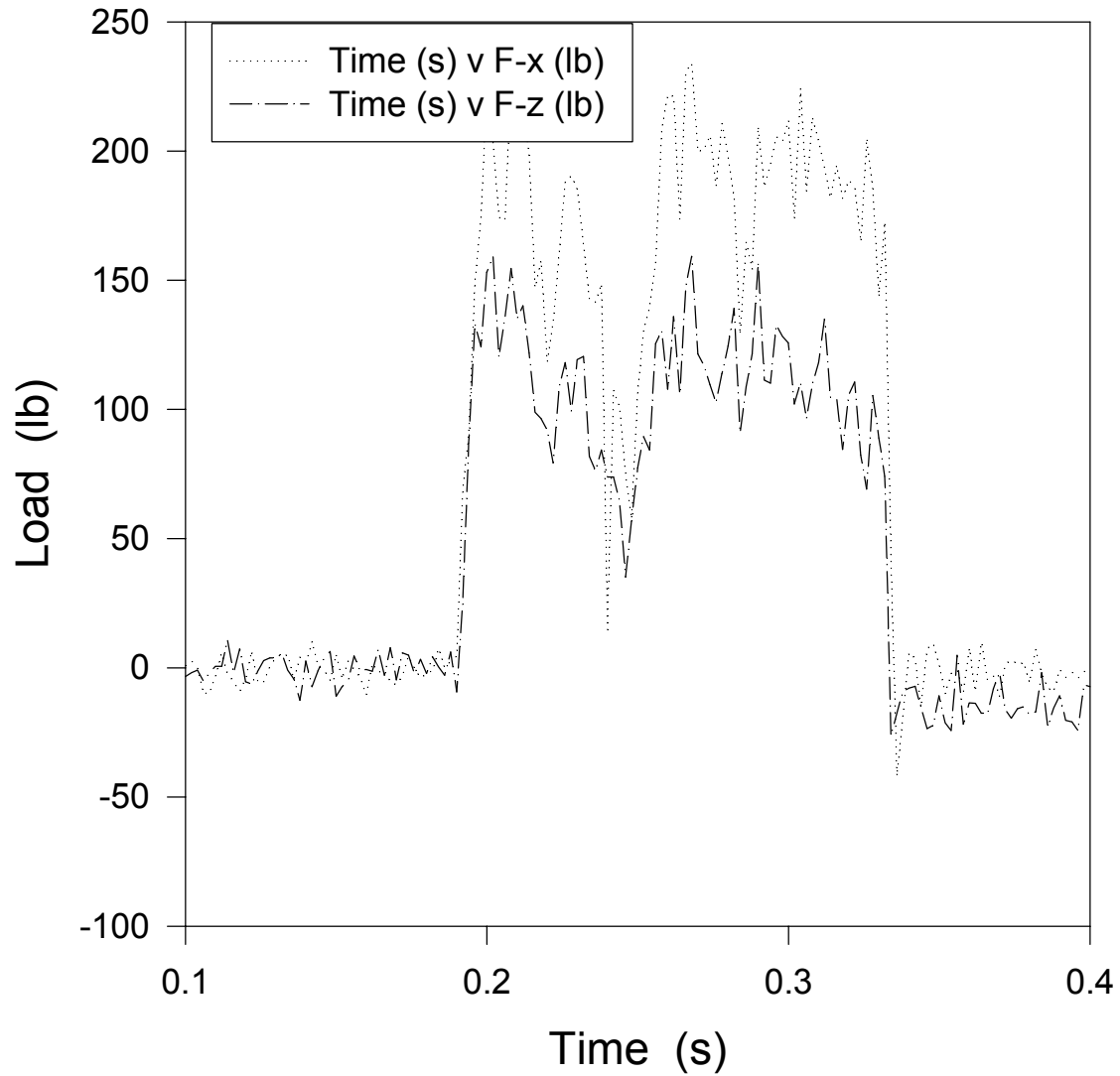


Figure B25: Sample S420-1 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Solid Sodium Chloride  
Delay Time: Twenty Minutes  
Horizontal Force:  $108 \pm 27$  lbs  
Vertical Force:  $172 \pm 145$  lbs

## S420-2

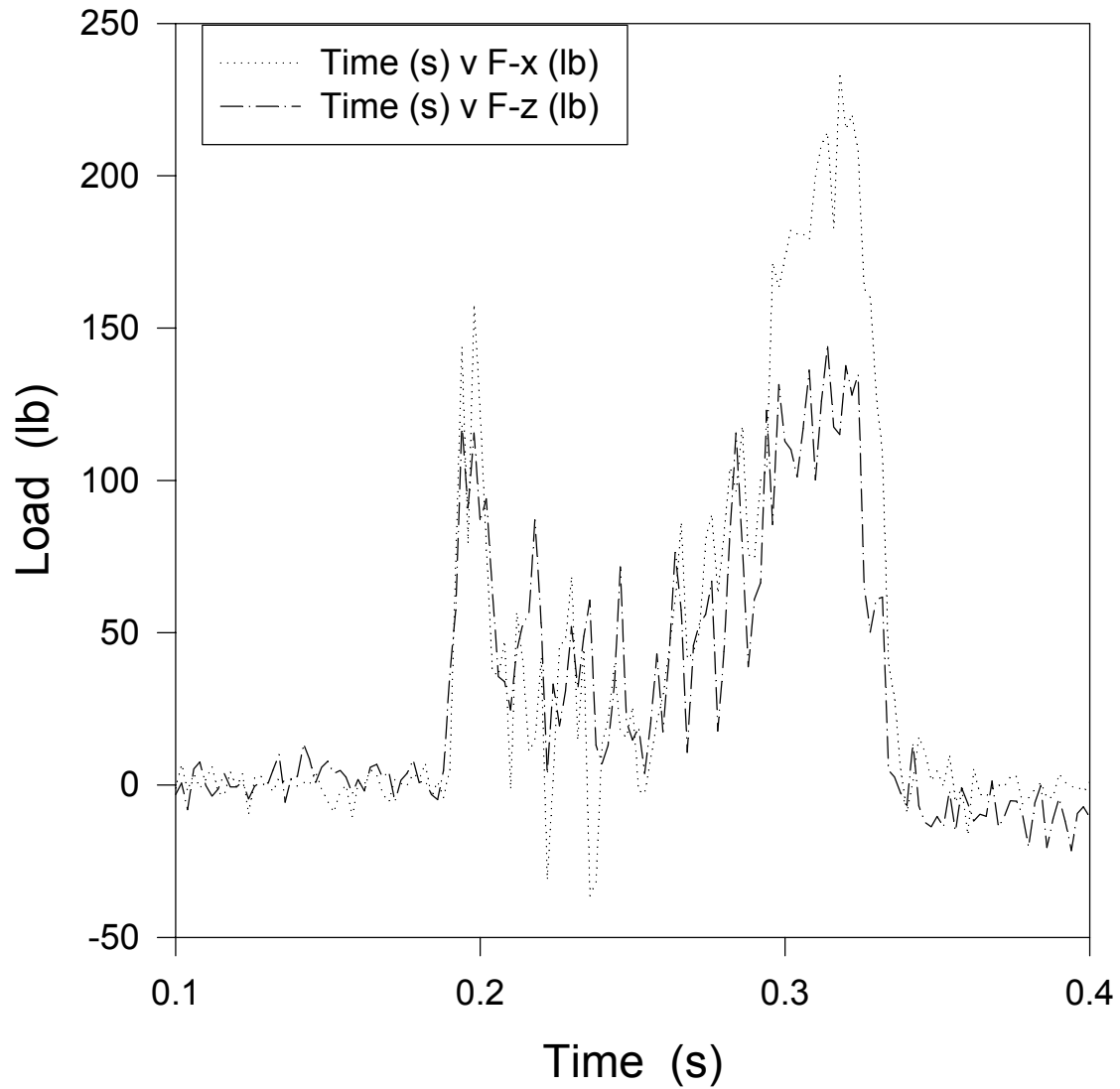


Figure B26: Sample S420-2 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Solid Sodium Chloride  
Delay Time: Twenty Minutes  
Horizontal Force:  $63 \pm 40$  lbs  
Vertical Force:  $83 \pm 71$  lbs

## S420-3

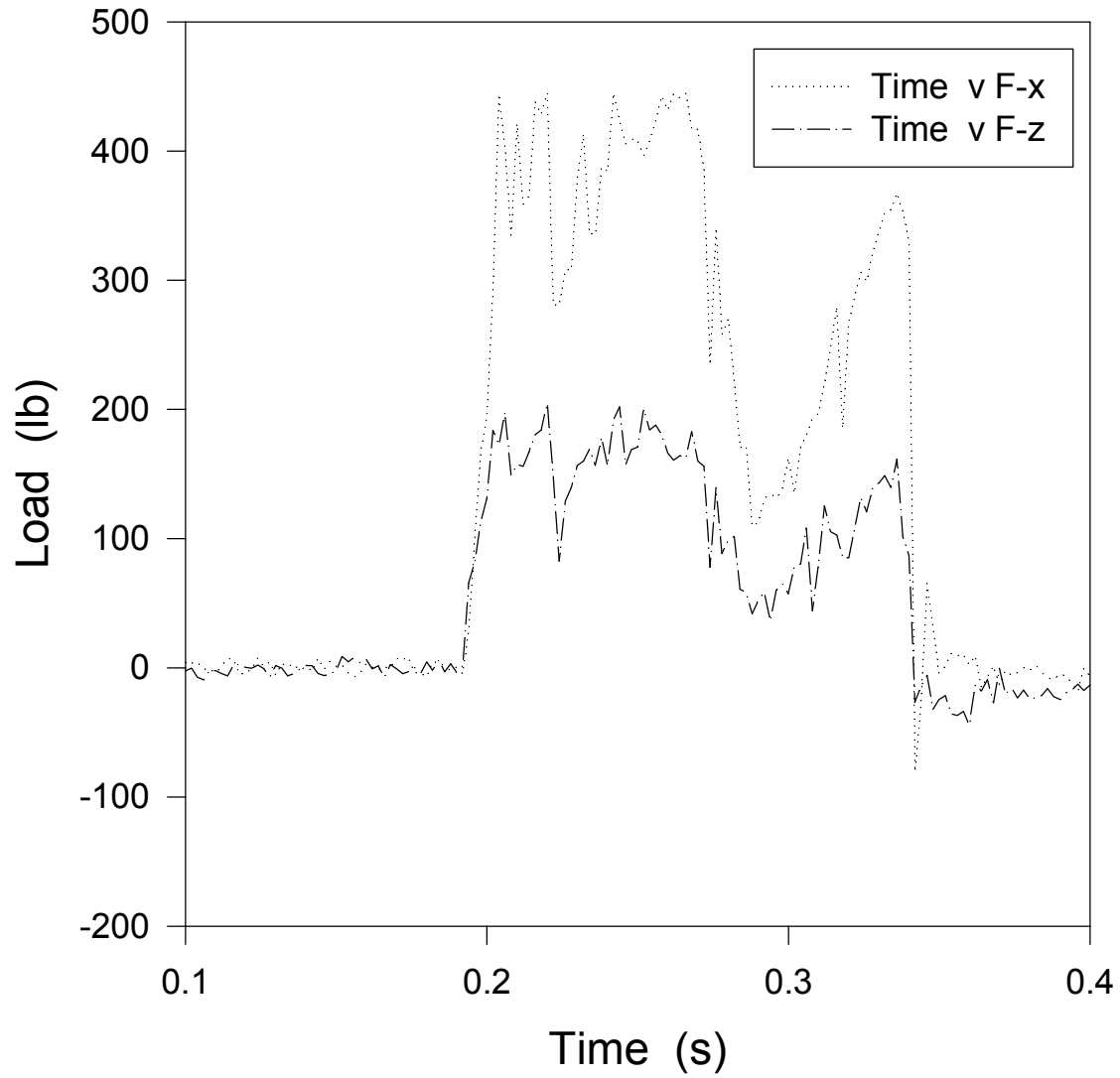


Figure B27: Sample S420-3 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Solid Sodium Chloride  
Delay Time: Twenty Minutes  
Horizontal Force:  $130 \pm 47$  lbs  
Vertical Force:  $305 \pm 111$  lbs

## S430-1

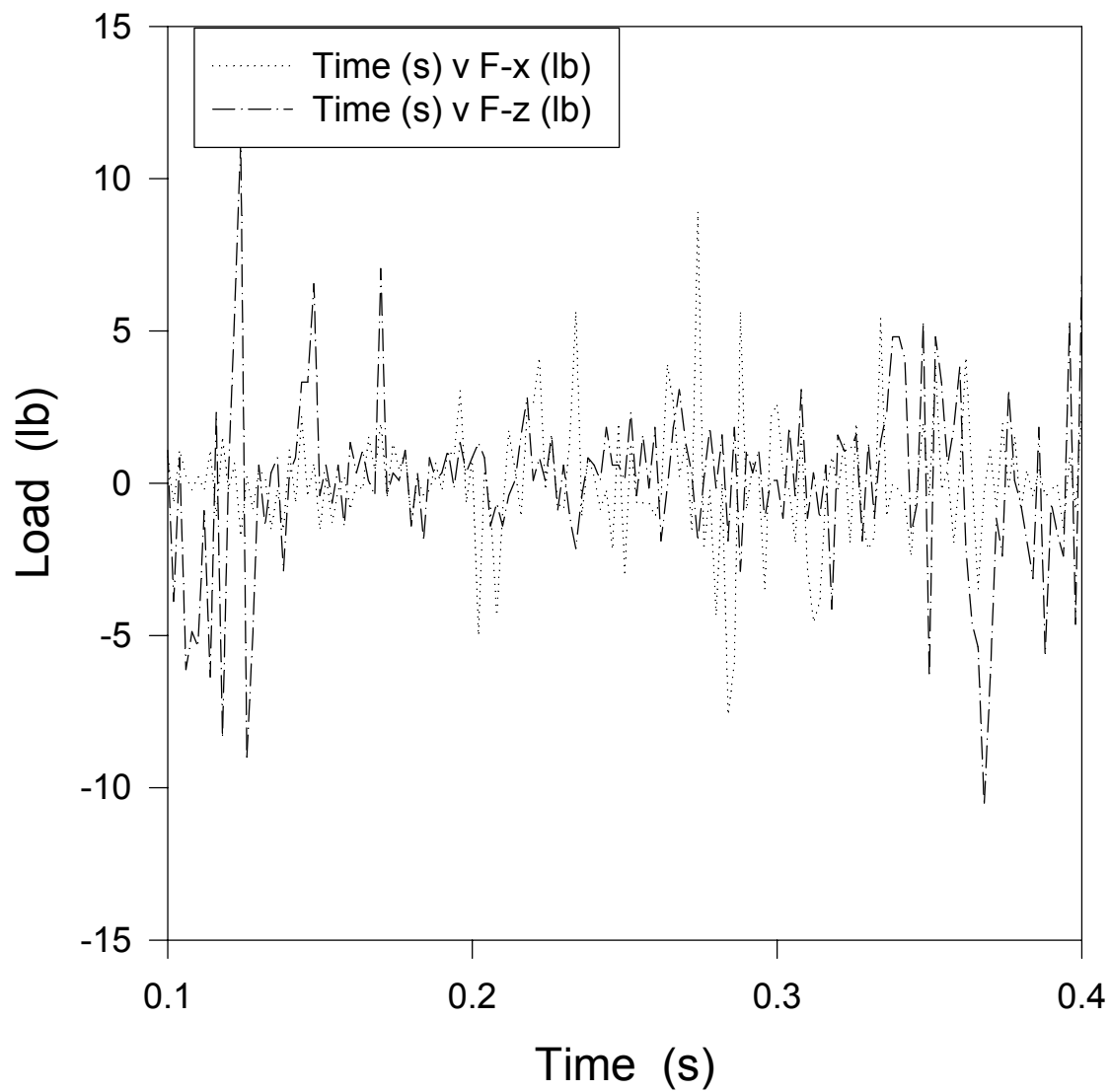


Figure B28: Sample S430-1 Load Trace  
Test: Zero Load Result  
Chemical Type: Solid Sodium Chloride  
Delay Time: Thirty Minutes  
Horizontal Force:  $0 \pm 1$  lbs  
Vertical Force:  $0 \pm 3$  lbs

## S430-2

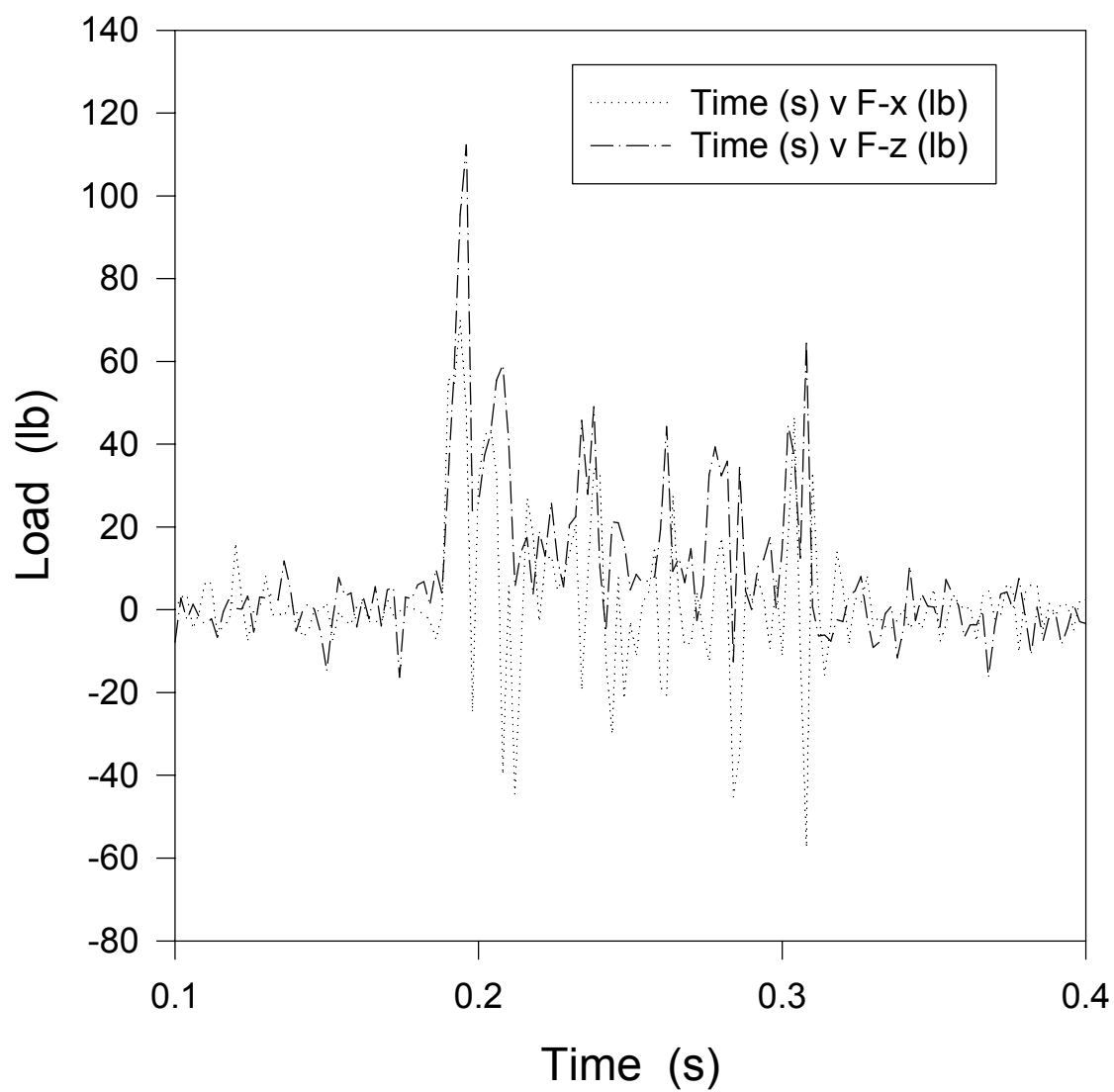


Figure B29: Sample S430-2 Load Trace  
Test: Zero Load Result  
Chemical Type: Solid Sodium Chloride  
Delay Time: Thirty Minutes  
Horizontal Force:  $24 \pm 23$  lbs  
Vertical Force:  $5 \pm 26$  lbs



## S430-3

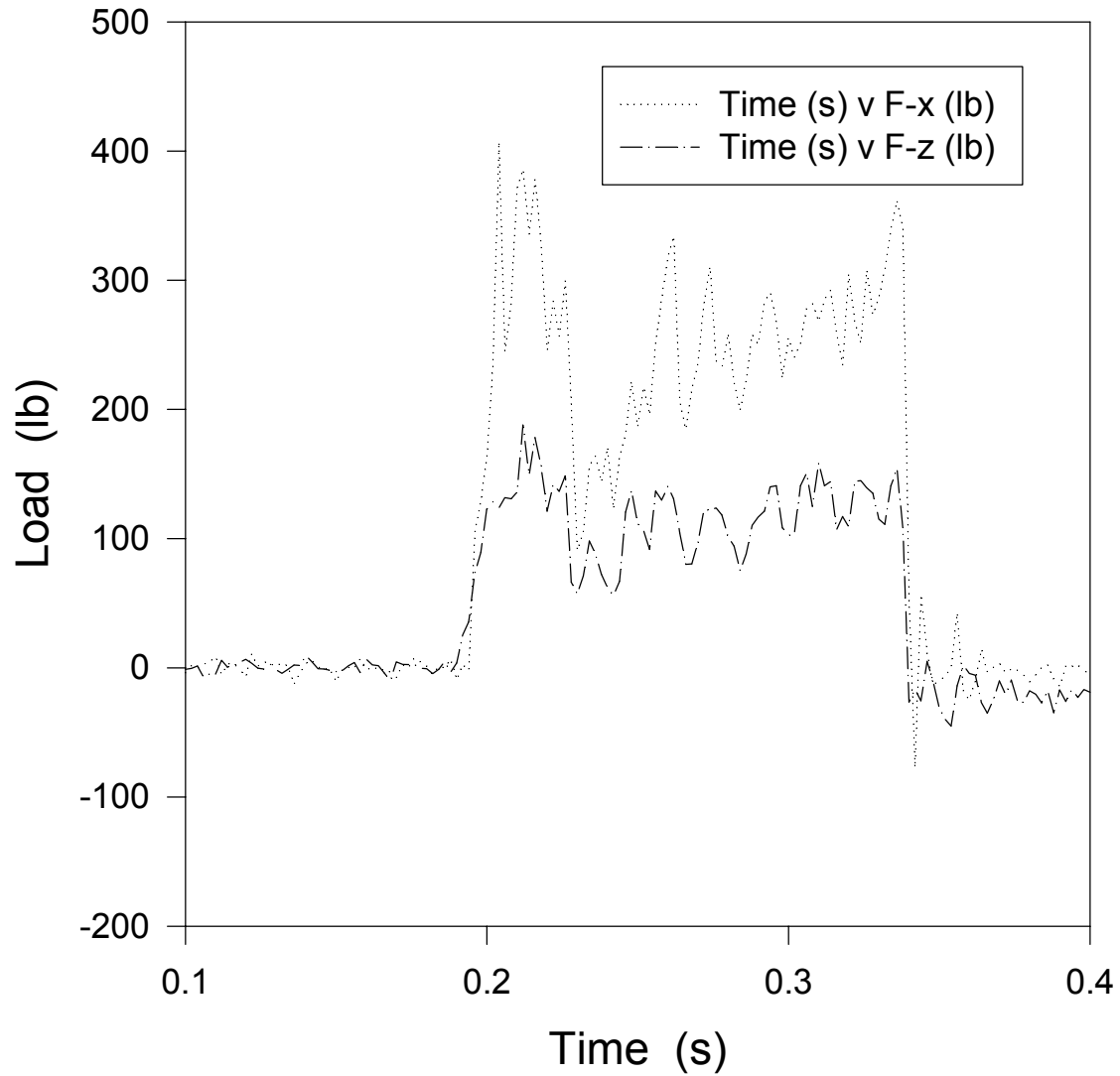


Figure B30: Sample S430-3 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Solid Sodium Chloride  
Delay Time: Thirty Minutes  
Horizontal Force:  $115 \pm 32$  lbs  
Vertical Force:  $244 \pm 79$  lbs

## S440-1

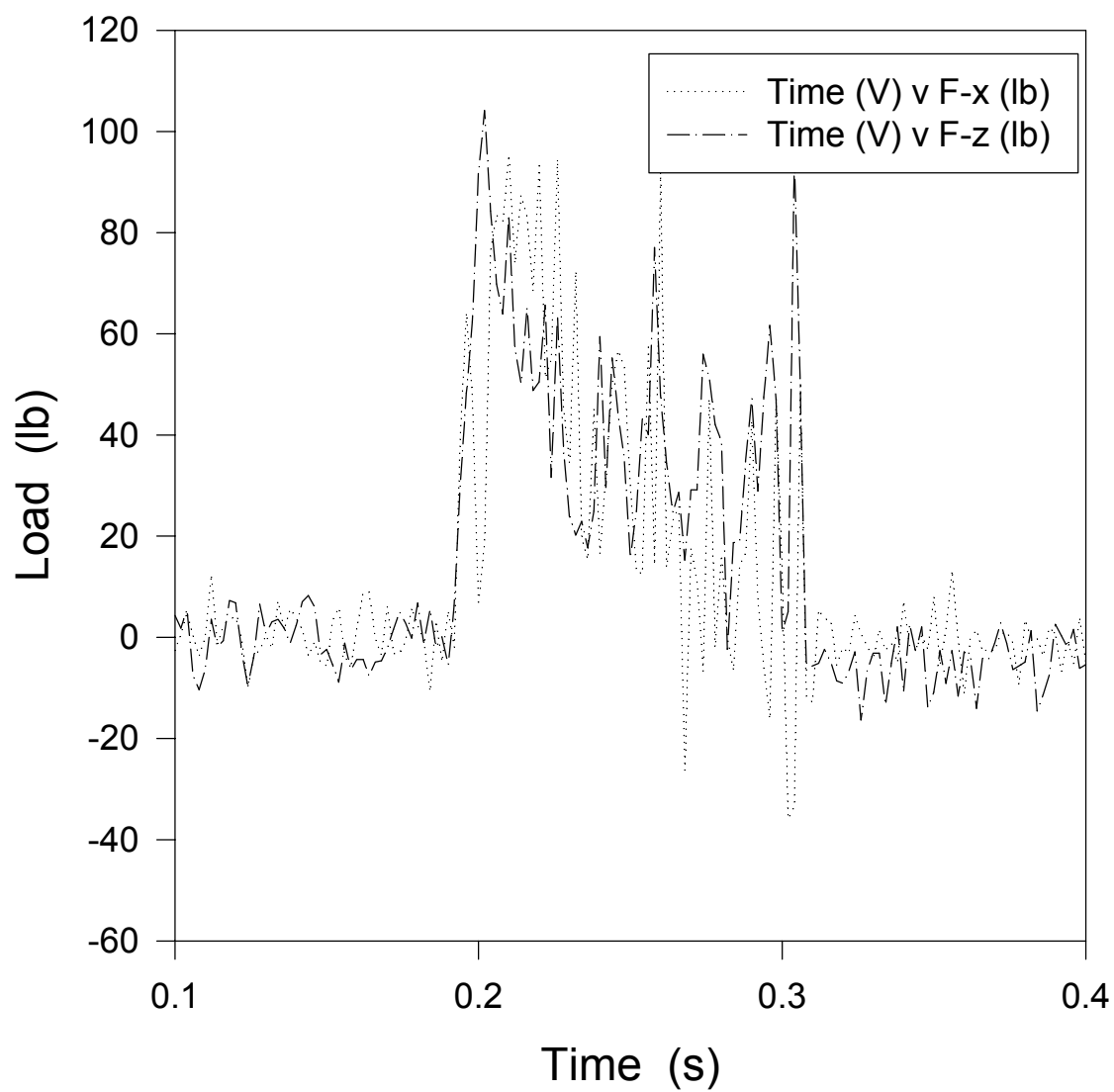


Figure B31: Sample S440-1 Load Trace  
Test: Non-Zero Load Result  
Chemical Type: Solid Sodium Chloride  
Delay Time: Forty Minutes  
Horizontal Force:  $44 \pm 23$  lbs  
Vertical Force:  $35 \pm 34$  lbs

## S440-2

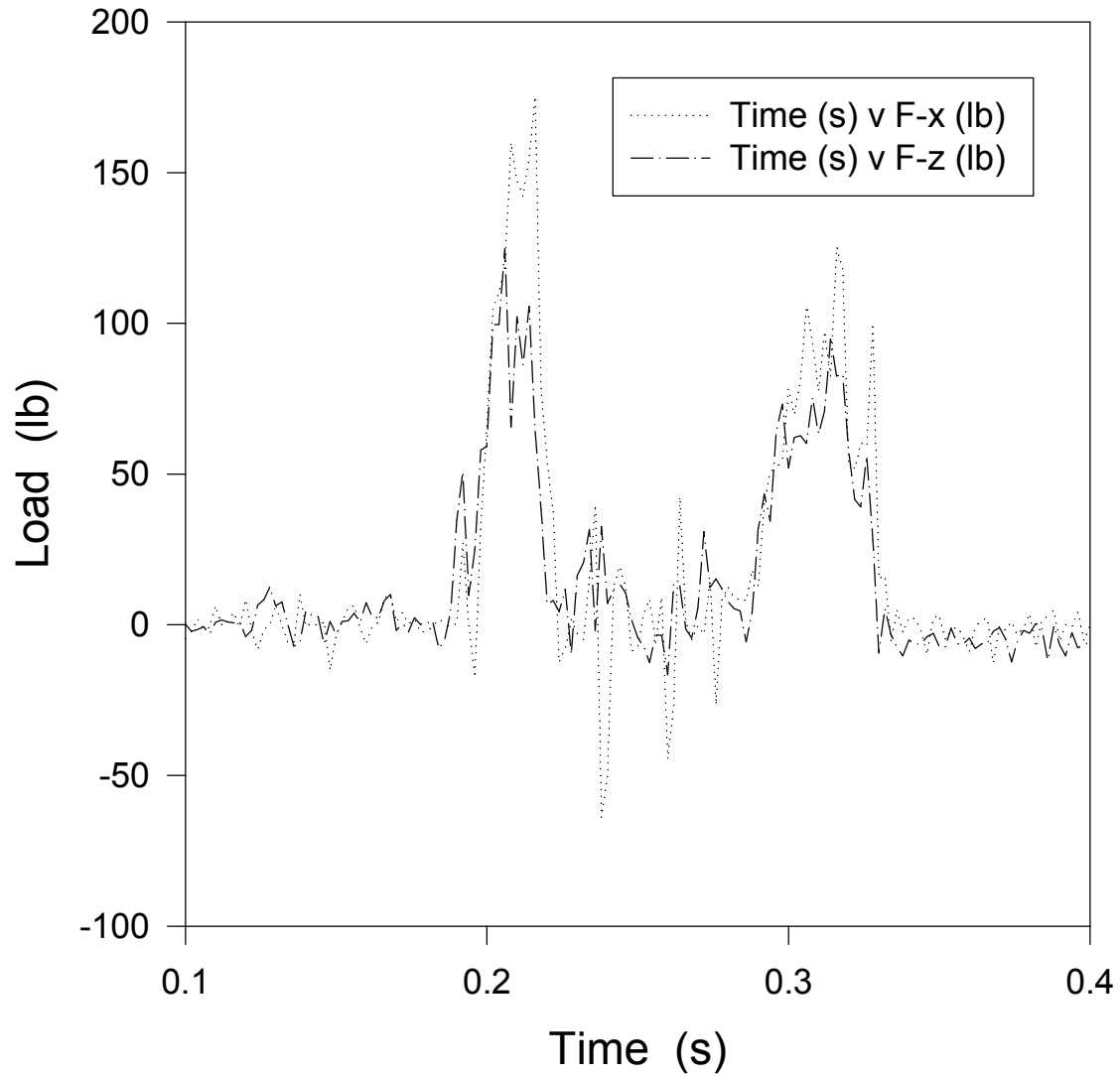


Figure B32: Sample S440-2 Load Trace  
Test: Zero Load Result  
Chemical Type: Solid Sodium Chloride  
Delay Time: Forty Minutes  
Horizontal Force:  $35 \pm 35$  lbs  
Vertical Force:  $40 \pm 54$  lbs

### s440-3

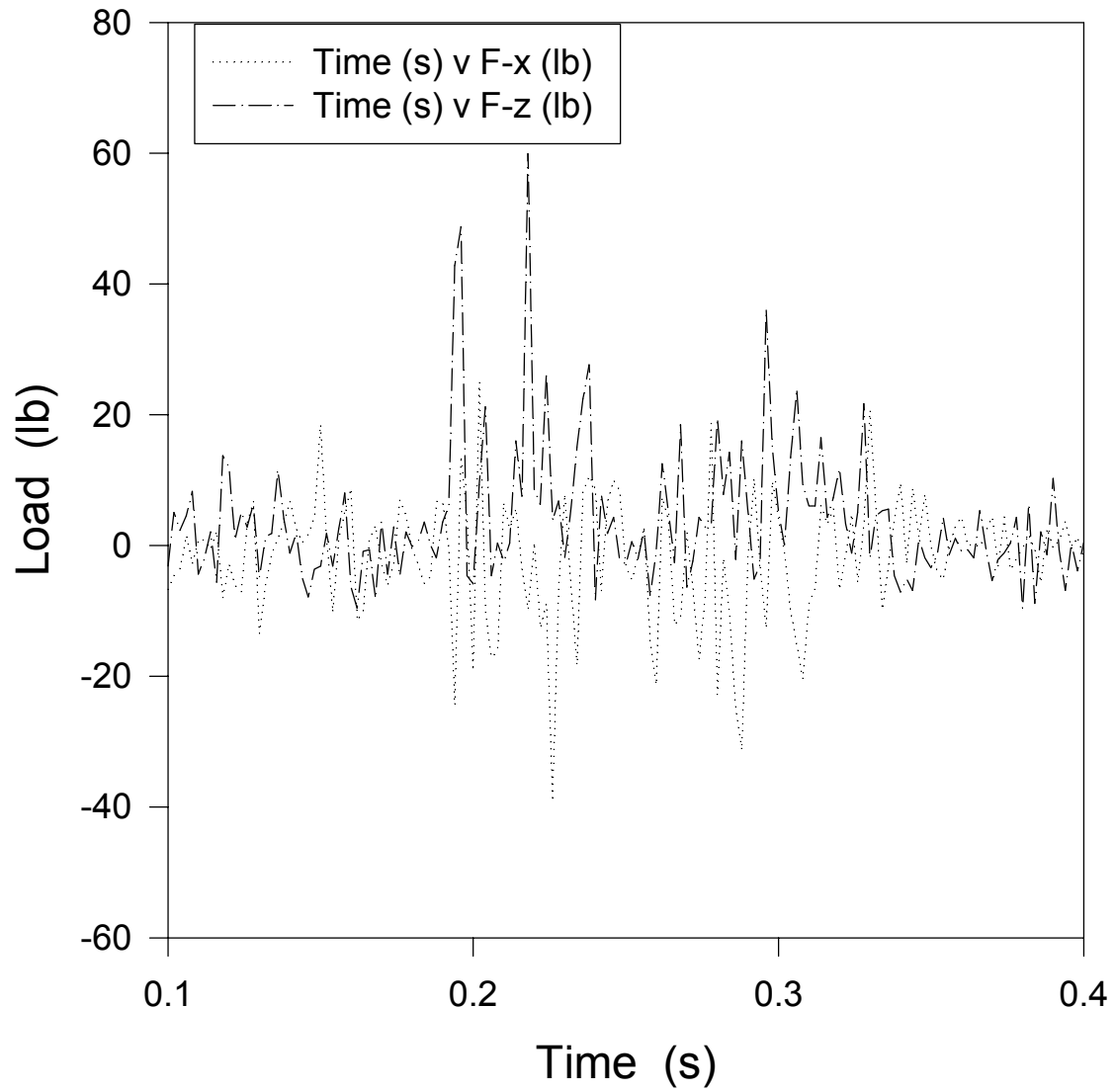


Figure B33: Sample S440-3 Load Trace  
Test: Zero Load Result  
Chemical Type: Solid Sodium Chloride  
Delay Time: Forty Minutes  
Horizontal Force:  $8 \pm 13$  lbs  
Vertical Force:  $-4 \pm 12$  lbs